JET PROPULSION

Journal of the

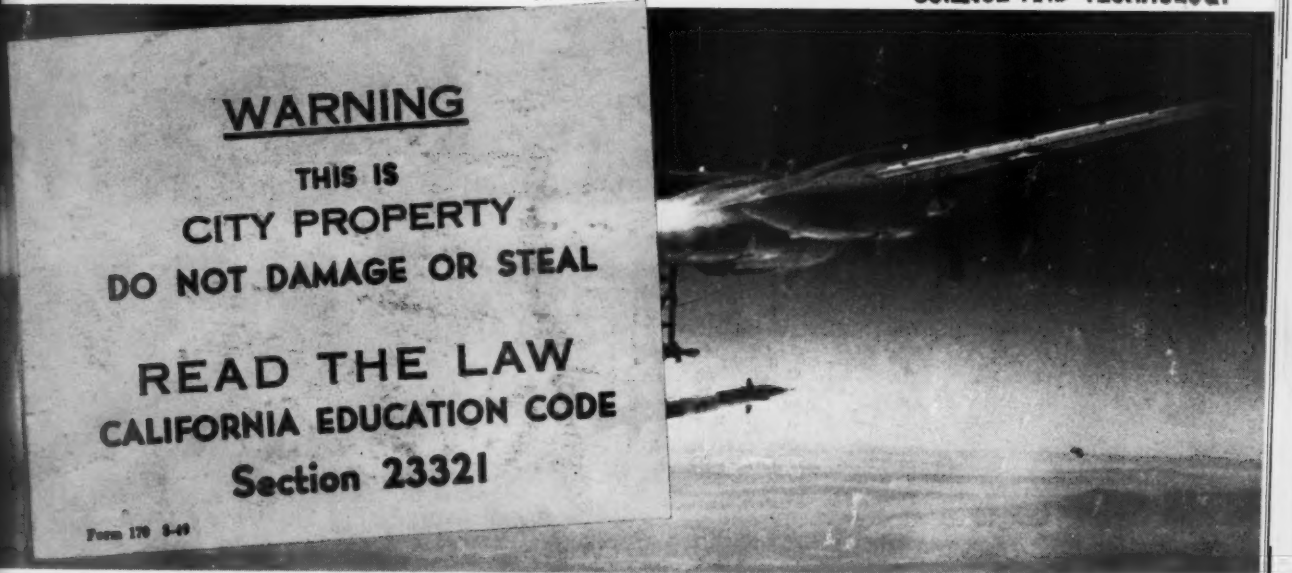
AMERICAN ROCKET SOCIETY

Rocketry . . . . Jet Propulsion Sciences . . . . Astronautics

STACKS

VOLUME 27 | FEBRUARY 1957 (In Two Parts) | NUMBER 2, PART 1

SCIENCE AND TECHNOLOGY



First photo of rocket-powered Shrike shows air-to-surface missile in test launching from B-29. Although smaller, Shrike is undisputed progenitor of rocket-powered Rascal now under development at Bell Aircraft . . . . . p. 184

Recovery of Rocket Powered Vehicles and/or Their Components . . *R. Provart* 125

Re-entry Heat Transfer to Satellite Vehicles . . . *N. H. Kemp and F. R. Riddell* 132

Molybdenum for High Temperature Strength . *R. R. Freeman and J. Z. Briggs* 138

Experiments With Cavitating Venturis . . . . *K. Berman and T. C. Carnavos* 148

A Generalized Closed Form for Burnt Velocity . *R. A. Struble and H. D. Black* 151

Rational Scaling Procedures for Liquid-Fuel Rocket Engines . . *S. S. Penner* 156

Similitude Considerations in Turbojet Engines . . . . . *S. Way* 162

Effect of Turbulence on Flame Radiation . . *R. R. John and M. Summerfield* 169

Technical Notes

Thermonuclear Power Plants + Earth-to-Mars Space Path + Reverse Jet Flameholders 176

Features

Missiles Boost Navy Striking Power 180

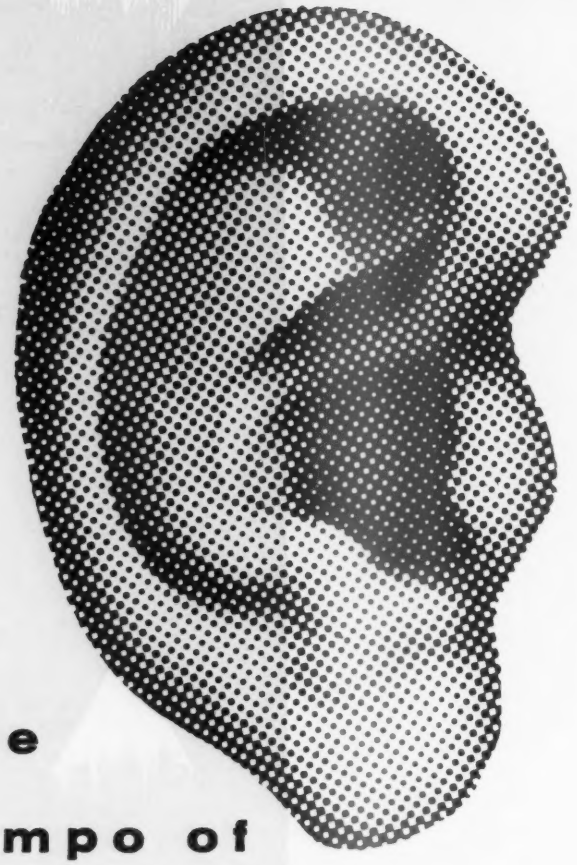
Dogs Aid Russian High Altitude Research 186

An American Reports on Soviet Science 200

Mysteries of Meteoritic Dust Begin to Unfold 207

Jet Propulsion News . . . 193, Space Flight Notes . . . 207, ARS News . . . 211, New Patents . . . 214

New Equipment and Processes . . . 218, Book Reviews . . . 223, Technical Literature Digest . . . 234



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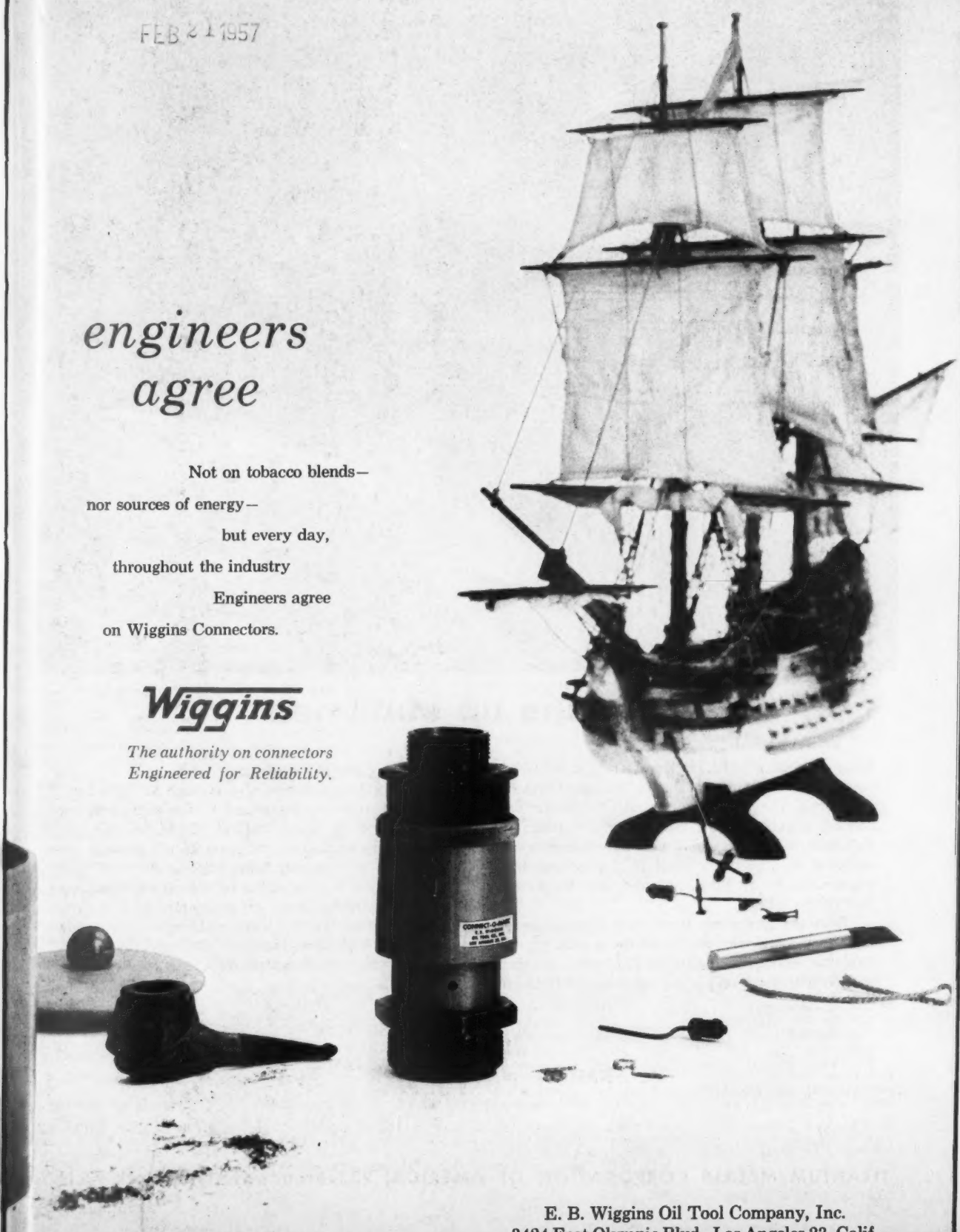

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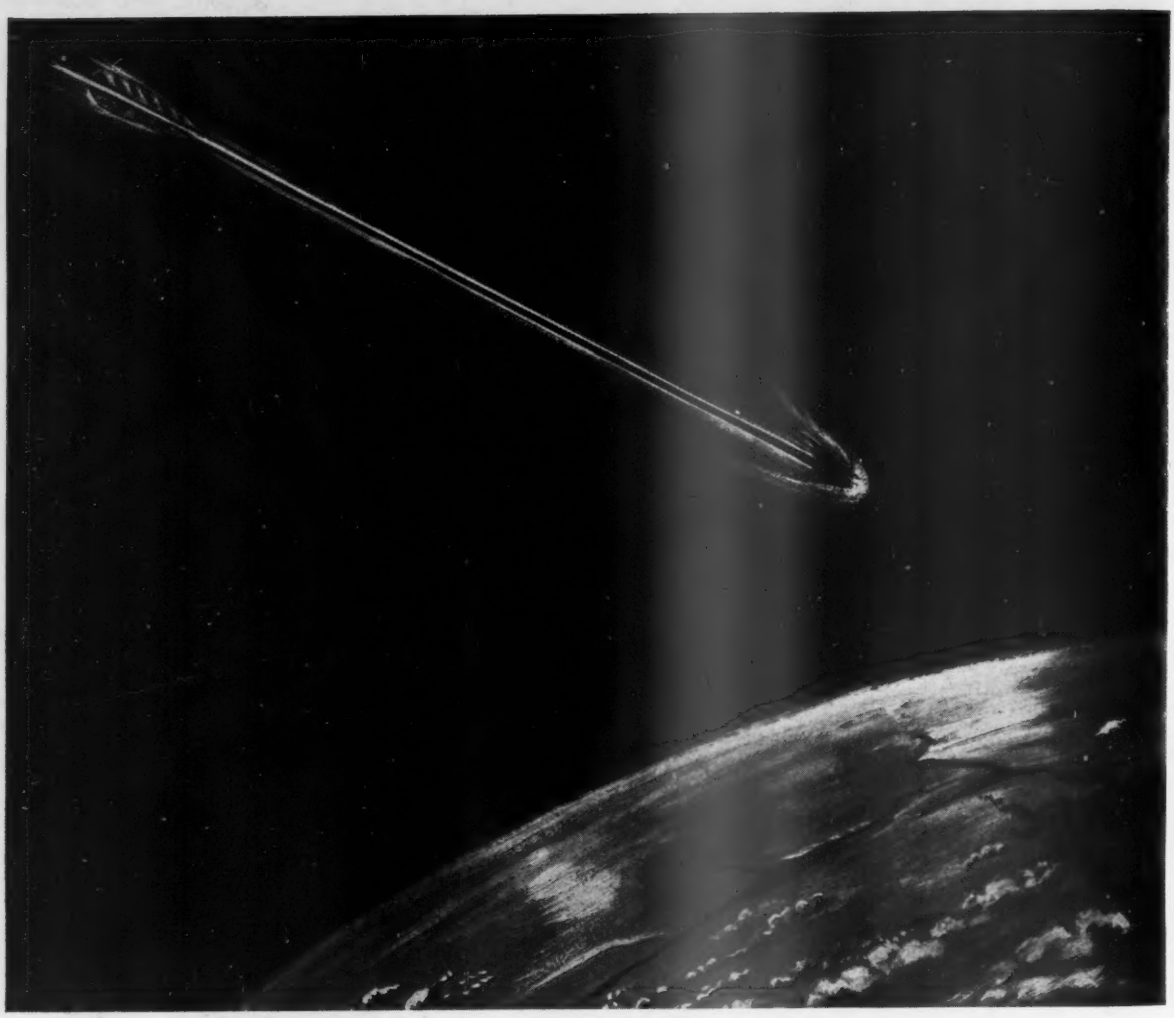

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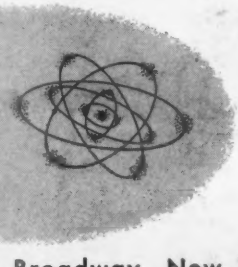

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JET PROPULSION, the Journal of the American Rocket Society, is devoted to the advancement of the field of jet propulsion through the publication of original papers disclosing new knowledge and new developments. The term "jet propulsion" as used herein is understood to embrace all engines that develop thrust by rearward discharge of a jet through a nozzle or duct; and thus it includes systems utilizing atmospheric air and underwater systems, as well as rocket engines. JET PROPULSION is open to contributions, either fundamental or applied, dealing with specialized aspects of jet and rocket propulsion, such as fuels and propellants, combustion, heat transfer, high temperature materials, mechanical design analyses, flight mechanics of jet-propelled vehicles, astronautics, and so forth. JET PROPULSION endeavors, also, to keep its subscribers informed of the affairs of the Society and of outstanding events in the rocket and jet propulsion field.

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JET PROPULSION, the Journal of the American Rocket Society, published monthly by the American Rocket Society at 20th and Northampton Streets, Easton, Pa., U.S.A. The Editorial Office is located at 500 5th Ave., New York 36, N. Y. Price $1.25 per copy, $12.50 per year for nonmembers, $6.25 per year for members: Entered as second-class matter at the Post Office at Easton, Pa., under the Act of March 3, 1879.

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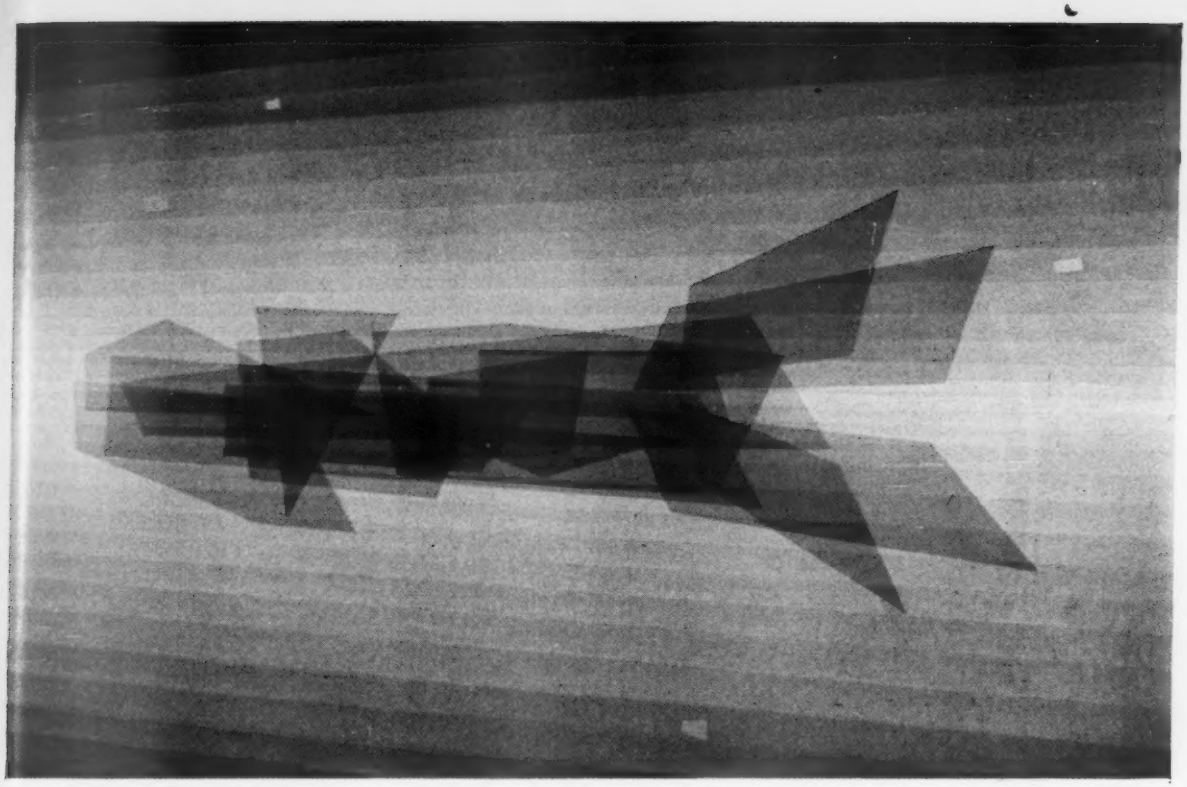

"ROCKETS", one of a series of paintings by Simpson-Middleman, a team of artists with the rare ability to translate scientific fact into creative imagery. Here, the rocket's blast and its guiding beam are thought of as a single stream of light through the center. Darks and lights of definite shape in a weak visual vector field are relied on to suggest the "wobble" caused by the acts of the servo-mechanisms in making their adjustments. Painting courtesy John Heller Gallery, Inc.

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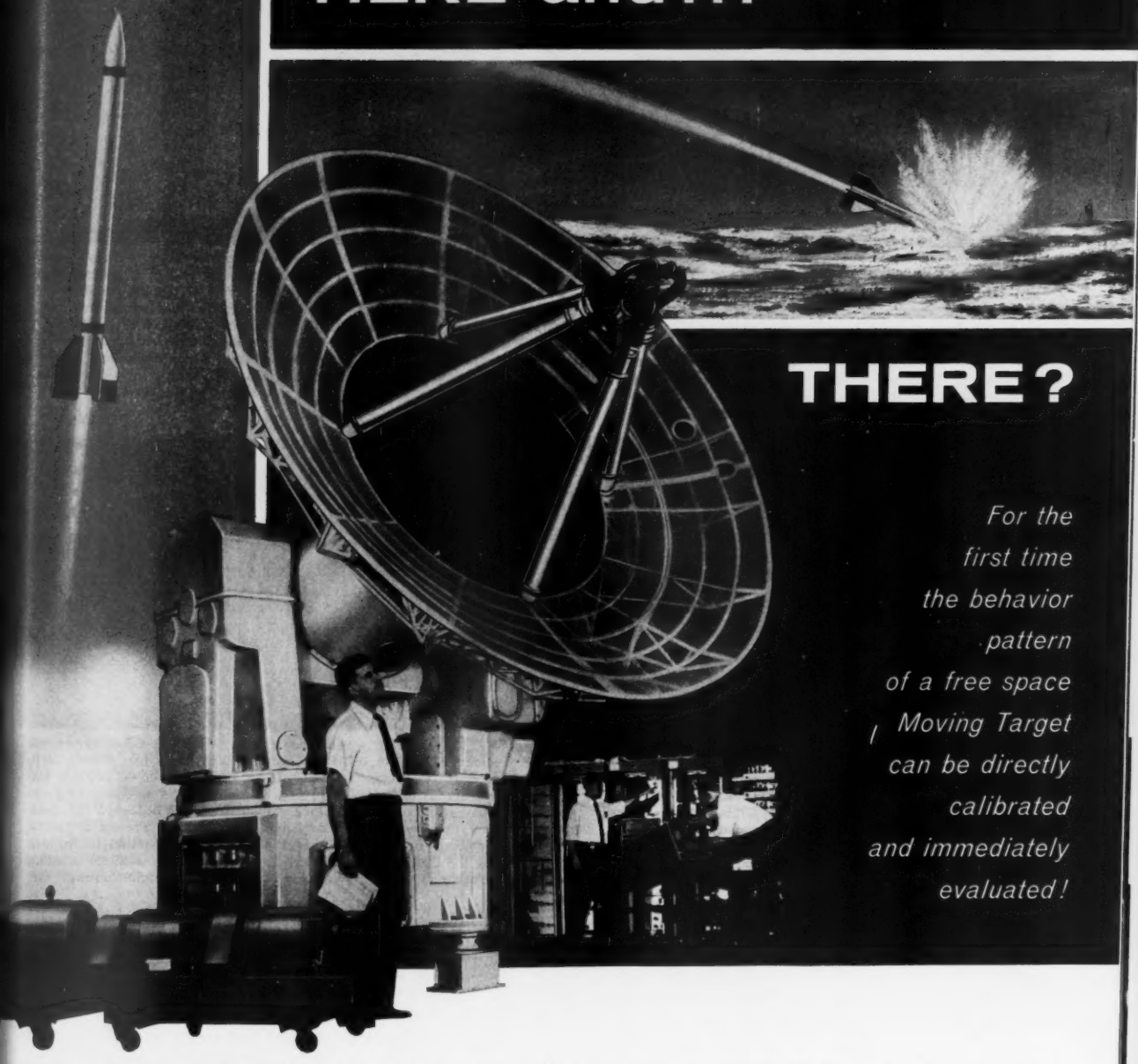

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Systems Evaluation Engineers test and evaluate electronic analog and transistorized digital computer systems design for aircraft; evaluate new systems and improvements to insure compliance with specifications and Air Force requirements. Other assignments: tie-in testing of peripheral equipment, liaison with design, development and field engineering. *Do you belong on this team?*

Harry Branning (center): B.S.E.E. 1950, Syracuse. Design Engineer in circuit design, 1951; October, 1954, promoted to Associate Engineer; April, 1956, promoted to Staff Engineer, Systems Planning. In June, 1956, appointed Project Engineer and Manager of the 110 Computer Circuit Design Department; discussing the performance and packaging details of a transistorized read amplifier.

William Dunn (standing): M.E. 1950, M.S.E.E. 1952, Stevens Institute. Technical Engineer, 1955; April, 1956, promoted to Associate Engineer; August, 1956, transferred to Development Engineering in charge of Logical Design for digital computers in advanced weapons systems; here discussing Boolean Algebra method of optimizing the logical design of an airborne digital computer.

Eli Wood (left): B.S.E.E. 1950, Connecticut. IBM Customer Engineer, July, 1950; September, 1952, transferred to ACL Field Engineering. February, 1954, in charge of Field Engineering at Hunter AFB; May, 1955, Associate Engineer; appointed Project Engineer, Manager of Systems Evaluation in August, 1956; here investigating a problem in radar data presentation set evaluation testing.

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Systems Analysts anticipate performance and recommend design criteria before and during development of equipment. Later, they compare dynamic performance accuracy and reliability characteristics with what has been anticipated. Other assignments include Digital Computer Systems Engineering, Input-Output and Analog-Digital Conversion Engineering. *Do you belong on this team?*

Quentin Marble (left): B.S.M.E. 1951, Syracuse. Joined IBM in 1951; promoted to Design Engineer in 1952; May, 1955, promoted to Associate Engineer, and then to Project Engineer, Manager of the Systems Coordination and Specification Group, Production Engineering Department, in February, 1956; shown here describing a unique cooling design to a new employee in his group.

Monroe Dickinson (left): B.S.E.E. 1952, W.P.I.; M.S.E.E. 1954, M.I.T. Technical Engineer in analog and alternate computer techniques for weapons systems, 1952; Associate Engineer responsible for systems design and analysis, 1954; December, 1955, Staff Engineer, responsible for research planning; here reviewing set-up on laboratory analog computer of a sampled data control problem.

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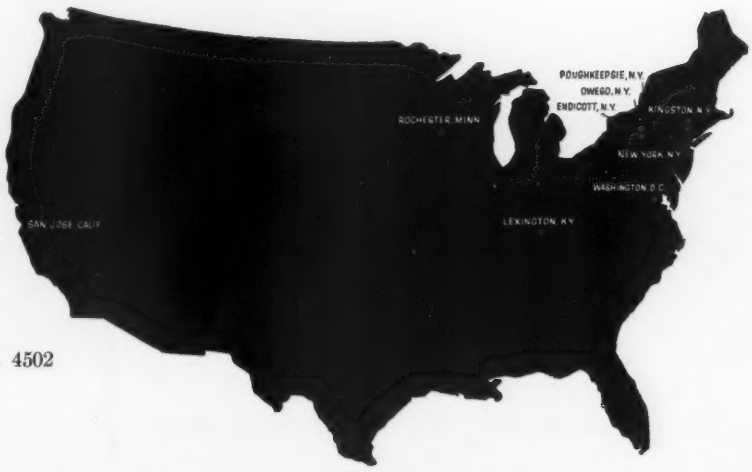

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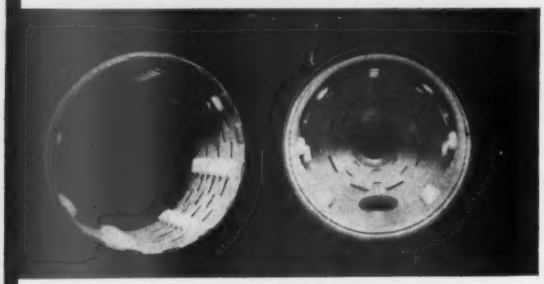

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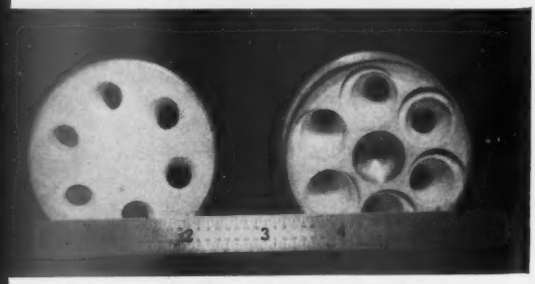

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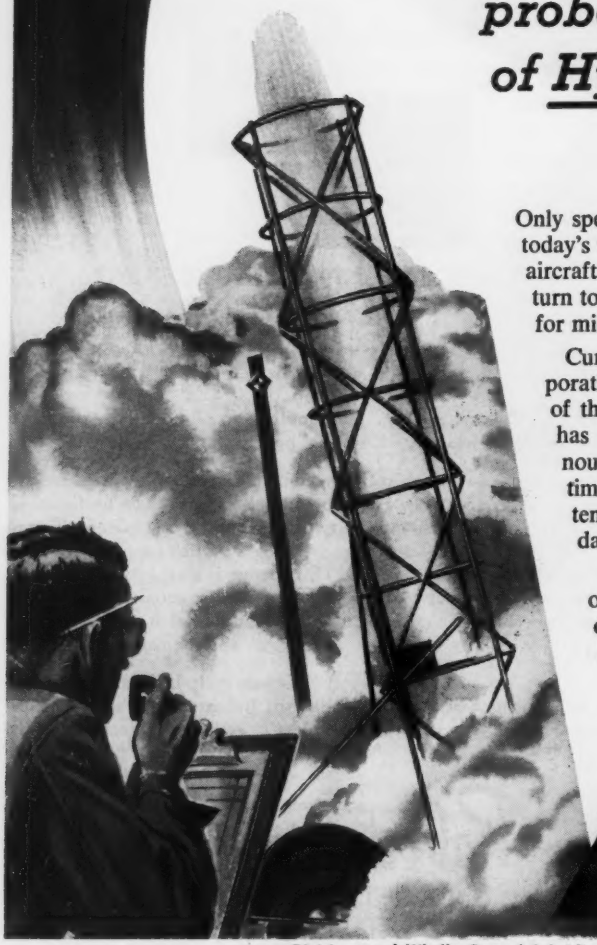

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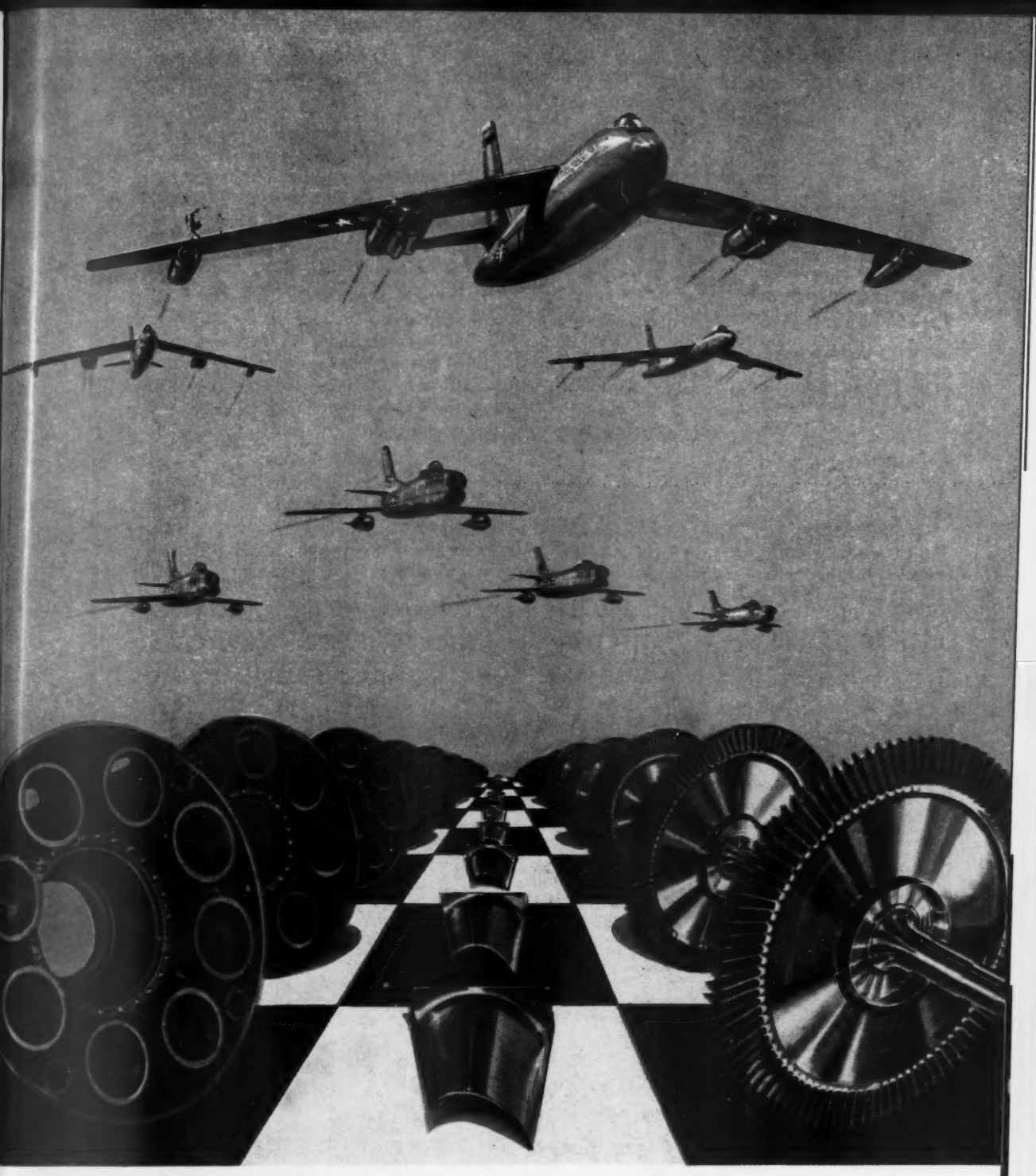

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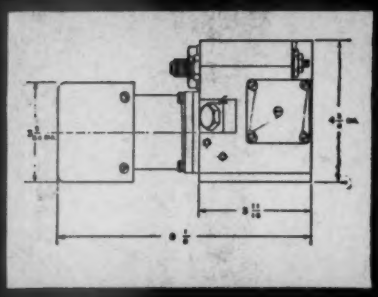
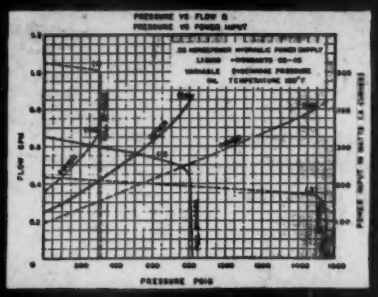
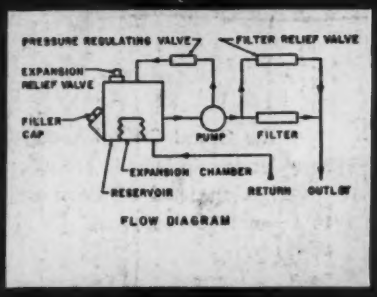
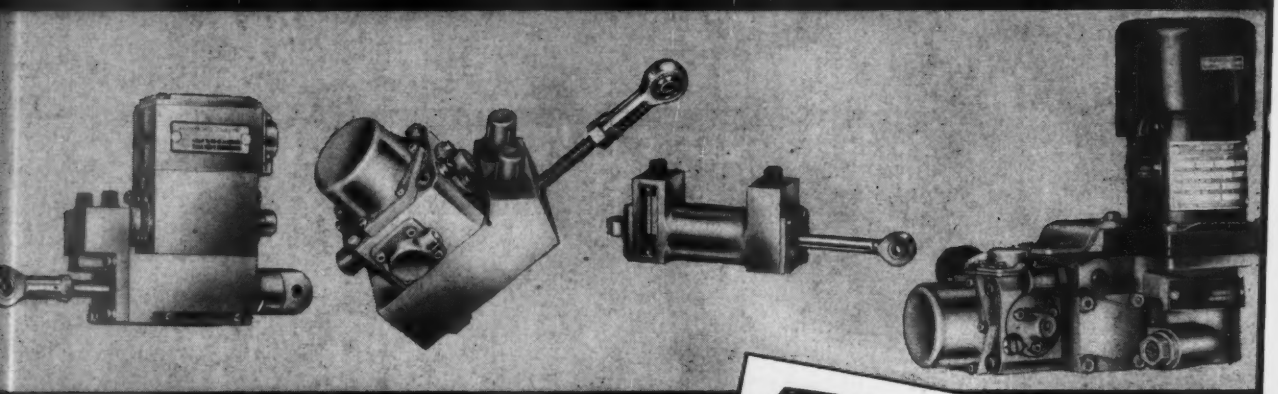






FLOW DIAGRAM



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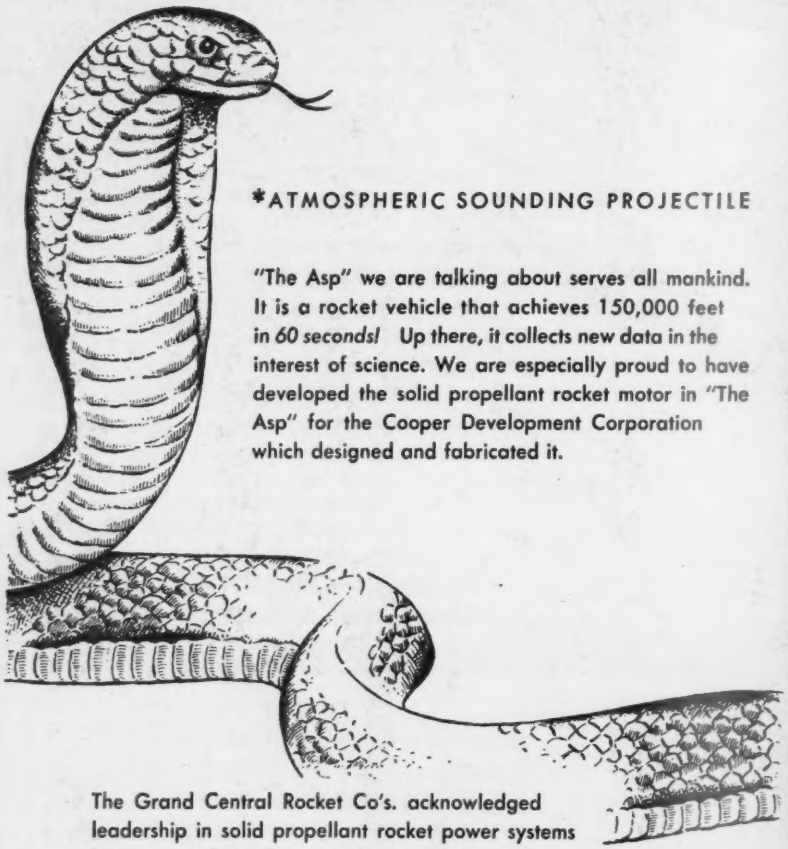

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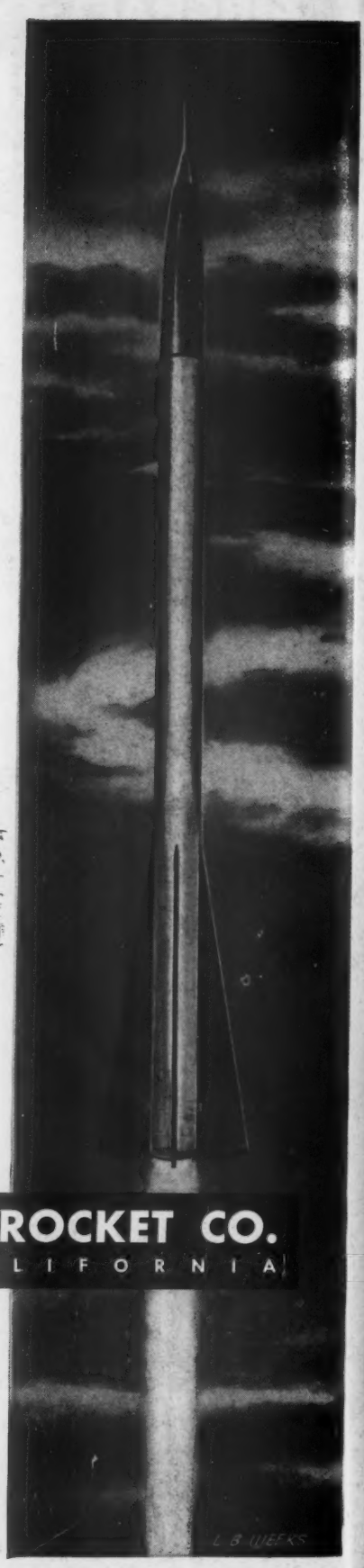

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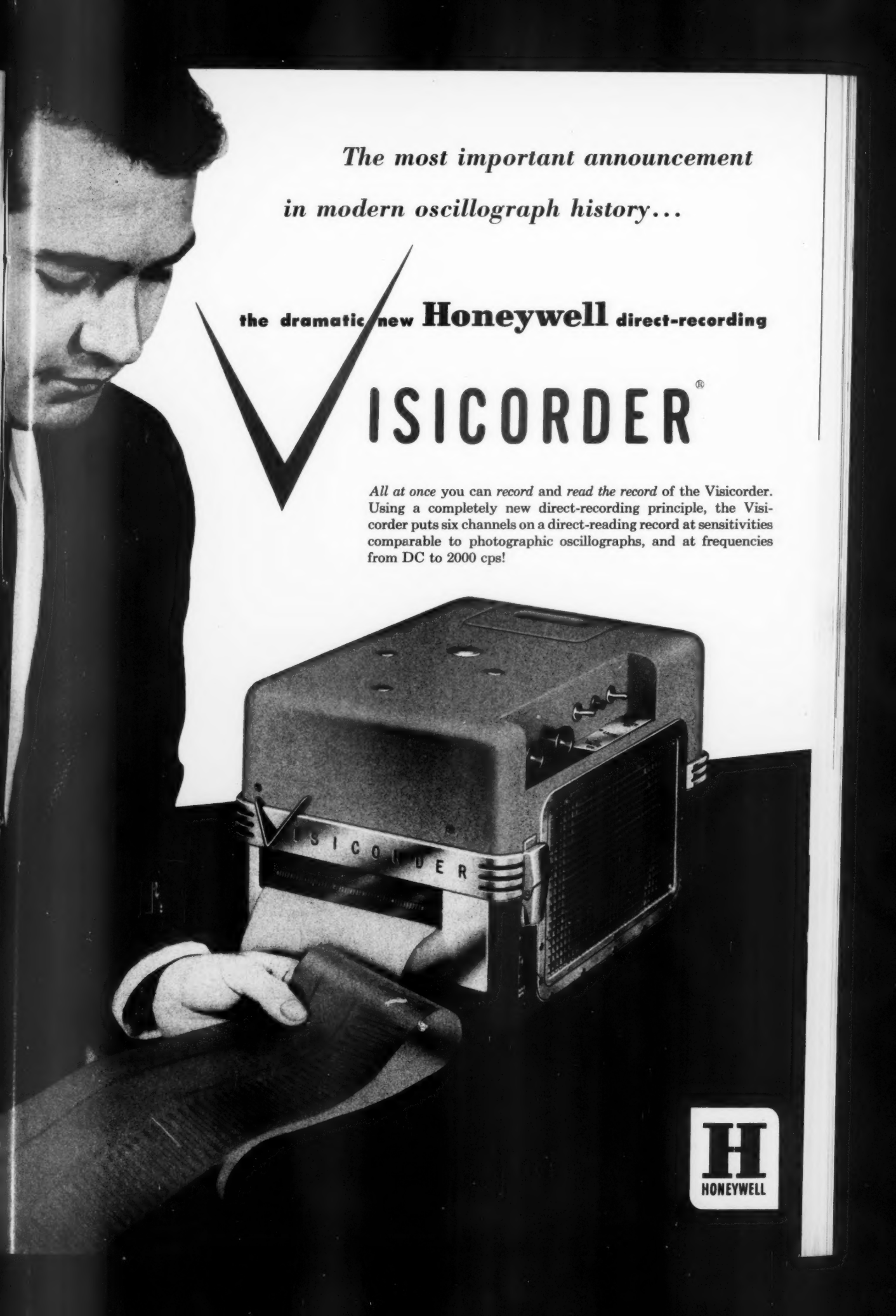
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THE **NEW** *VISICORDER,* perfected after years of research by the Heiland Division of Honeywell, combines the high frequency and high sensitivity characteristics of photographic oscillographs with the convenience of a direct-recording instrument.

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Visicorder records are reproducible by several methods using commercially available equipment.

Since the Visicorder operates on light-beam galvanometers, traces may deflect the full 6″ width of the chart, peak to peak, and their deflection is not limited by adjacent channels.

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FREQUENCIES	From DC to 2000 cps without peaked amplifiers or other compensation of any kind.
SENSITIVITIES	Comparable to photographic-type oscillographs.
RECORDING METHODS	Records directly on paper which requires no powder magazines, liquids, vapors, or other processing. Records are immediately visible and usable. Daylight loading. Accommodates recording paper 100 feet in length. Indicator shows unused recording paper available.
NO. OF CHANNELS	6 channels on 6″ wide paper plus provisions for two timing traces.
DEFLECTION	Full 6″ peak to peak. Traces may overlap; not limited by adjacent channels.
RECORD SPEEDS	0.2, 1, 5, and 25 inches per second, minute, or hour.
GALVANOMETERS	D'Arsonval-movement mirror galvanometers with choice of natural frequencies to suit individual requirements.
AMPLIFICATION	None required for most applications.
POWER	115 volt 60 cycle AC operation. 4 amperes.
DIMENSIONS	10″ height; 15″ depth; 10″ width.
WEIGHT	37 pounds, complete and ready to operate.
PRICE	$2,500.00, less galvanometers. Galvanometers $150.00 each.

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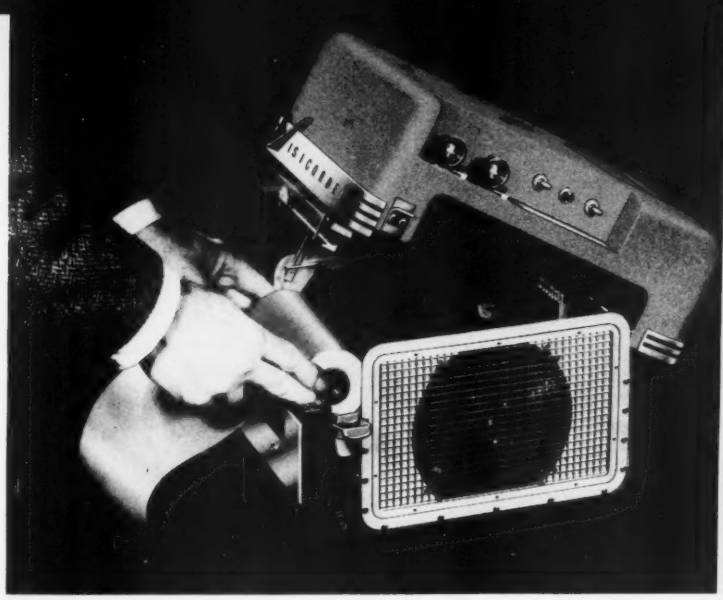
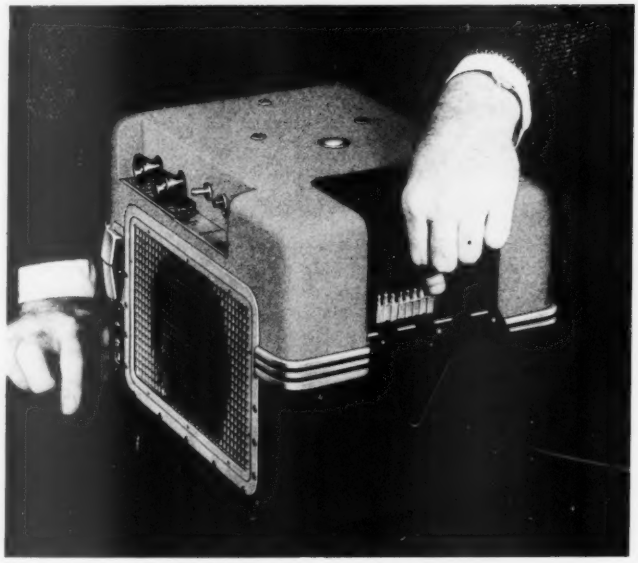
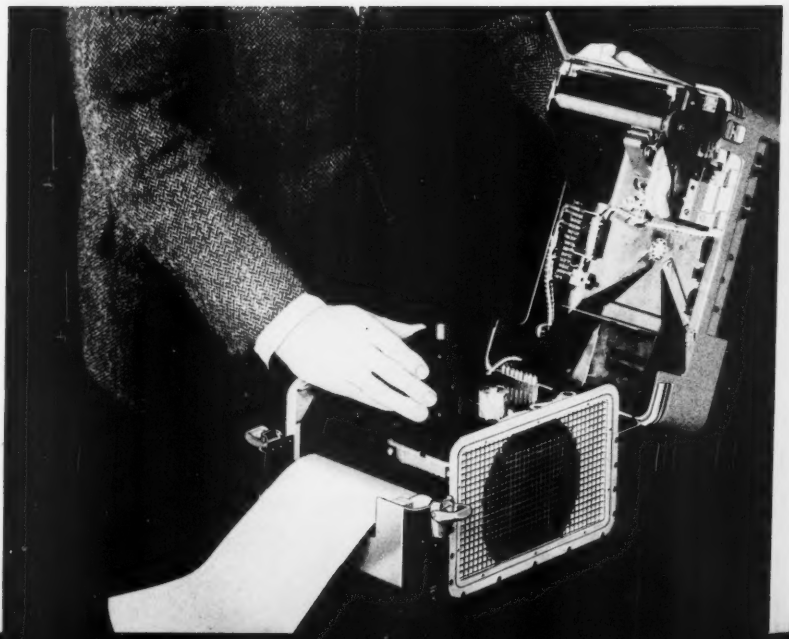
❶ *THE VISICORDER* is the first and only photographic-type oscillograph that can be loaded with recording paper in daylight. The paper speeds can be selected while the instrument is in operation. The light spots from the galvanometers are *visible from the exterior* at their point of contact with the paper; thus phenomena can be monitored simultaneously with their recording.





❷ *GALVANOMETER ADJUSTMENTS* may be made through a panel-covered opening in the back of the instrument. Other operating controls —power on-off, lamp switch, paper drive and paper speed—are located on one convenient panel. Galvanometers are of the familiar Heiland solid-frame type: high sensitivity, accurate balance, high stability, low drift, in a versatile range of frequencies and sensitivities.

❸ *SERVICE* on the Visicorder is extremely easy, since the instrument opens completely as shown. All components—galvanometers, recording lamp, transmission—are completely accessible.



VISICORDER® APPLICATIONS

The versatile Visicorder will fit almost unlimited applications because of its high frequency and sensitivity characteristics, and because of its ease of operation.

In any application where instantaneous monitoring is needed, whether or not a record is desired, the Visicorder is ideal.

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★ **In PILOT and COMPONENT TESTING,** the Visicorder will accomplish more rapid evaluation of design and prototypes than any other direct-writing oscillograph available.

★ **In MEDICAL** applications the Visicorder is useful for dynamic blood pressures, electrocardiograms, EEG, and other physiological measurements.

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FEBRUARY 1957

VOLUME 27 NUMBER 2

JET PROPULSION
Journal of the
AMERICAN ROCKET SOCIETY

Editor-in-Chief

MARTIN SUMMERFIELD

The Recovery of High Speed Rocket Powered Vehicles and/or Their Components

ROBERT PROVART[1]

Cook Research Laboratories, Skokie, Ill.

Basic considerations of the recovery problem are presented, and details peculiar to the types of components to be recovered are noted. A discussion of the velocity, time, altitude, attitude (spinning, tumbling, etc.), and other trajectory conditions during which recovery may be initiated and/or effected is included. Various techniques of programming a recovery system are outlined and the methods of sensing environmental conditions which are pertinent to the recovery sequence are indicated. Several braking devices, their operation, advantages, and disadvantages are described. Recovery systems are compared through the use of efficiency, limitation, complexity, and reliability parameters. The presentation is summarized with a commentary on the range of application of parachute technology as it stands today. Devices and/or materials which appear to be promising for future use, and the problems associated with each of these, are indicated.

1 The Basic Recovery Problem

THE conditions of the basic recovery problem may vary considerably. The type of unit which is to be recovered may, in general, be classed in the following categories:

A Complete Assemblies

Recovery may be required for a complete vehicle which may possess a very low C_0 (deceleration coefficient: $C_0 = \frac{1}{2}\rho \cdot (C_D A/M)$). For such a configuration the recovery problem is perhaps the most difficult, because most of the deceleration must be effected by the recovery device.

B Component Subassemblies

In this category may be placed such items as the initial power stages of multiple stage rocket vehicles for which intermediate values of C_0 would be generally representative. Accordingly, the recovery problem is somewhat relieved.

C Vital Packages or Payloads

Vital packages (such as instrumentation and cameras) or payloads (such as atmosphere samples and test subjects) may be jettisoned and recovered separately while the major vehicle frame is expended. For such jettisonable packages the general ranges of C_0 may be high and the recovery problem accordingly simplified.

The term C_0 (deceleration coefficient) has been used above. The value of C_0 will vary directly as C_D (drag coefficient) which, in turn, is dependent upon the vehicle shape and velocity. Fig. 1 illustrates some typical approximated curves of C_D vs. N_M (Mach number) for several configurations of vehicle using identical reference areas. This figure illustrates the wide range of values possible, even for a single shape (1).[2]

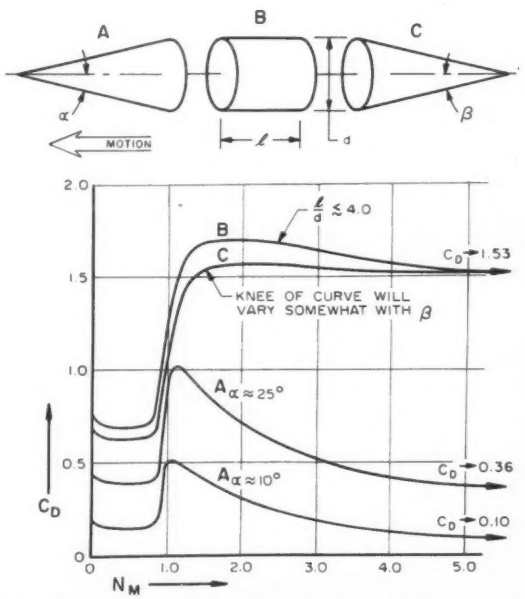


Fig. 1 The variation of drag coefficient with Mach number for several configurations of equal reference area

2 Recovery Conditions

The primary objective of any recovery sequence, of course, is the reduction of the vehicle or component velocity to some value for which adequate impact survival may be realized. It may be required to initiate the recovery at any one of a variety of interrelated conditions. Further, for identical starting conditions, the subsequent behavior of two vehicles of differing shape and mass may differ by a considerable amount.

To illustrate this point further the flight of two vehicles, A and B (whose characteristics are described below), is compared for a hypothetical case. If the major vehicle A carries the smaller unit B inside of it and ejects it at a predetermined time, then the conditions of motion of the two vehicles are identical until the moment of separation. If the vehicles are not similar then their behavior during flight, subsequent to separation, will be quite different.

Presented at the ARS Fall Meeting, Buffalo, N. Y., Sept. 24–26, 1956.

[1] Project Engineer, Aerophysics Section.

[2] Numbers in parentheses indicate References at end of paper.

For this illustration the vehicles have been assumed to follow a ballistic trajectory to velocities and altitudes such that, at the moment of ejection of B from A, the velocity, altitude, and direction of flight are 18,000 fps, 150,000 ft, and 30 deg below the horizontal, respectively. These are typical re-entry conditions.

The weight of configuration A is 4000 lb, and the reference area is 25 sq ft with an assumed shape such that the variation of C_D vs. N_M is that of curve A in Fig. 1. The weight of configuration B is 50 lb and the reference area is 1 sq ft with an assumed shape such that the estimated variation of C_D vs. N_M is that of curve B in Fig. 1.

Trajectories were calculated for the two vehicles and are shown in Fig. 2. Presented are altitude vs. range, velocity, acceleration, and time. It will be noted that the maximum accelerations are in the same order but that the lighter vehicle slows down much more rapidly and begins its approach to terminal conditions at an altitude almost twice that of the heavier vehicle (2).[3]

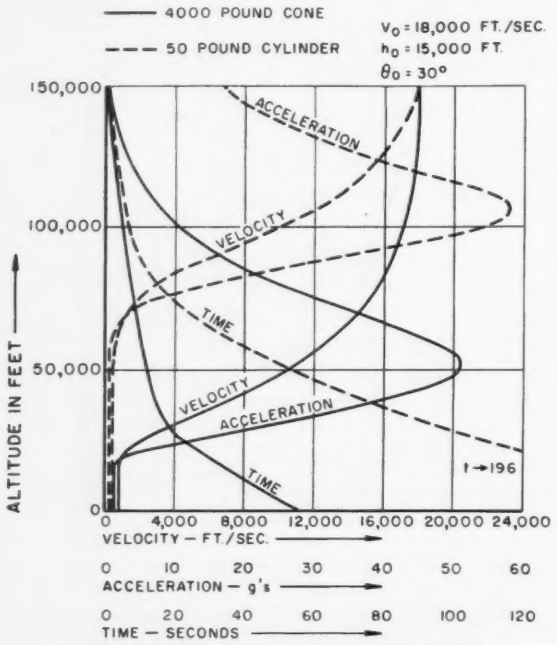


Fig. 2 Trajectory history for two vehicles of different configuration and weight, but for identical initial conditions

Other factors of significance to the recovery operation are stability, attitude, and temperature. The relative importance of the former two factors is dependent upon the type of recovery equipment to be utilized and is, therefore, not discussed here. The temperature problem is discussed in some detail in the latter section dealing with braking devices.

3 Programming Techniques

A specific general purpose programming system does not exist. As has been indicated before, the conditions for which recovery must be effected have considerable variation. The characteristics and performance of the specific vehicle to be recovered must be known.

Useful parameters for conducting the events which are to occur during a typical recovery sequence are:

t	= time	q	= impact pressure
y	= altitude	N_M	= Mach number
V	= velocity	n	= g acceleration

combinations of the above

[3] All trajectory information generated for this paper was calculated with the use of the data presented in (2).

For the case of hypersonic re-entry conditions, it is unlikely that pressure sensing devices will be practical. Consequently, programming systems which depend upon sensing altitude, velocity, impact pressure, or Mach number by such methods may not be used.

Programming systems using timers as the sole method of sequencing the recovery events may be used, providing the initial time event can be accurately selected. This may be accomplished by ground stationed computers and associated tracking equipment, and a radio link to communicate the initial event signal. Expanding this, the ground equipment may program the entire sequence as the vehicle is in flight.

Recovery of a vehicle may be required at some time while it is out of range of the ground equipment. In such an event, the system indicated above would be of no avail. In addition to this, the complexity of such a technique and the corresponding possibility of failure is great.

The use of the acceleration forces as the triggering media for events in the recovery sequence appears attractive. This phenomenon is illustrated in Fig. 2, in which the acceleration is shown to peak to over 50 g at altitudes of approximately 50,000 and 100,000 for the hypothetical vehicles A and B, respectively.

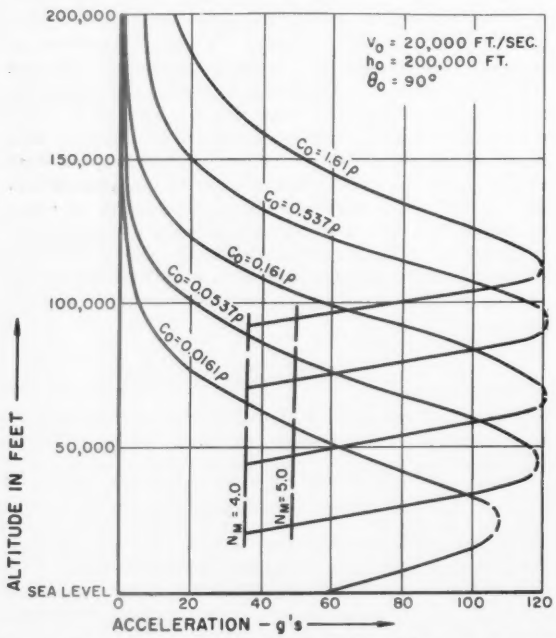


Fig. 3 Several plots of acceleration against altitude for a range of constant values of C_DA/M, but for identical initial conditions

A further illustration of this effect is given in Fig. 3. The curves are plotted for several constant values of C_DA/M which are considered representative of rocket powered vehicles. The initial conditions for all of the curves are typical of the re-entry case and are 20,000 fps vertically downward at 200,000-ft altitude.

Examination of Fig. 3 reveals that the curve shapes are similar in form. The low altitude side of each "g-hump" is a steep gradient of acceleration change per foot of altitude. Acceleration switches which operate at set values within ±10 per cent would indicate maximum approximate errors of ±1000 ft and ±2000 ft for desired operation at 50 g and 100 g, respectively. Expected errors may actually be much less because acceleration switches may be constructed with greater accuracy than this. However, precautions must be taken to prevent actuation of such switches for accelerations which are a result of tumbling or rotation of the vehicle.

The magnitude of the maximum deceleration, which seems

to vary in a direct fashion as the vertical component of velocity, is inconsequential within the structural limitations of the vehicle and its equipment. In general, for identical starting conditions of velocity, altitude, and angle of flight path just prior to re-entry, the "g-hump" will occur at altitudes varying in some inverse manner as the magnitude of C_0, the deceleration coefficient.

Values of C_D are relatively constant for velocities greater than that corresponding to $N_M = 5$ for many shapes, as indicated in Fig. 1. Consequently, the curves are extended only to values slightly less than this, or $N_M = 4$. It is observed, as shown in Fig. 2, that the acceleration will remain at easily measurable levels for velocities lower than $N_M = 5$, and so the use of acceleration switches for programming purposes in many cases is feasible at velocities which are subsonic.

4 Impact Survival

Before the requirements of a braking system can be established an understanding of the maximum impact survival possibilities is needed. Factors of importance here are: (a) the topography of the impact region, (b) the acceleration limits of the vehicle, and (c) the problems of locating the vehicle after impact.

A Land Impact

Collapsible nose structures may be used to absorb energy at impact. The design of such a nose will depend upon the acceleration limits and impact velocity of the vehicle and its cargo.

The vehicle nose may be fitted with a spike which, upon penetrating the soil, would absorb the kinetic energy of the vehicle. The decelerative forces of such a device may be controlled by proper length and shape of the spike and nose. A typical use of such an impact device is shown in Fig. 4, which illustrates Skokie, a test vehicle built by the Cook Research Laboratories of Skokie, Ill., for the purpose of testing missile recovery parachutes. Proper functioning of such an energy absorption method is dependent upon knowing the characteristics of the soil in which the vehicle will land. Ideal conditions for this are desert regions. Obviously, if the vehicle impacts in a region where rocks or gravel are abundant, a spike and nose shape designed for sand penetration will be of little use.

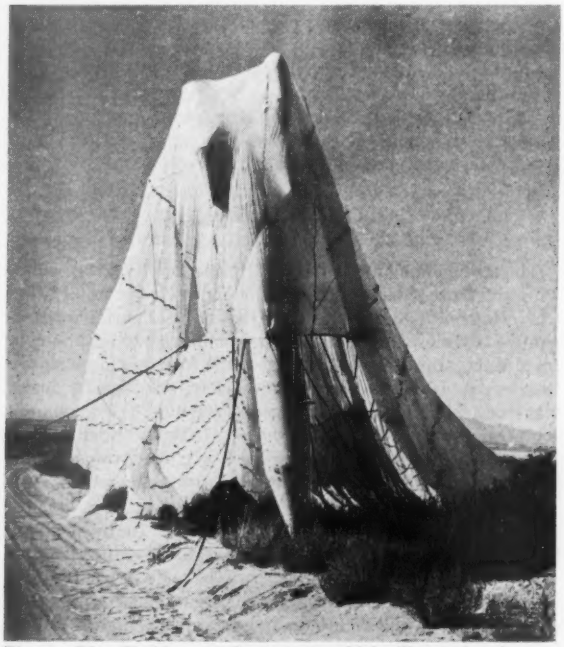


Fig. 4 The Skokie parachute test vehicle illustrating impact survival by means of spike and nose penetration in sand

If adequate control of the attitude of the vehicle is possible, retro-rocket power may be employed to reduce the impact velocity to safe magnitudes. For conditions where the required reduction of velocity is great, such a technique may require prohibitive quantities of fuel and so reduce the useful payload of the vehicle.

Where recovery regions are available having uniform characteristics and uniformly varying elevation, such as vast dry lakes, desert regions, or snow field areas (or water as noted below), a vehicle may be recovered by ricocheting. This would involve control of the vehicle flight path to achieve impact angles which have been selected on the basis of the acceleration limits and velocity at impact. Such a violent recovery method, of course, requires suitable ruggedness of the vehicle and its cargo.

B Water Impact

Since a large portion of the earth's surface is water, which possesses relatively uniform density and elevation, the oceans are suggested as recovery regions. Additional problems associated with water recovery are flotation and the protection of equipment which could be damaged by water (sea water). The solution to both of these problems is watertight sealing of the vehicle. However, if the sealed vehicle does not displace an adequate volume of water to provide buoyancy for its weight, then additional flotation techniques must be employed.

Since water recovery is considered to be the most generally applicable method, the recovery of the hypothetical vehicle A, as described earlier, is considered in greater detail in the following example:

The missile so described will displace approximately 40 cu ft of water when submerged. The net weight of the submerged vehicle is therefore approximately 1440 lb. Consequently, a flotation device must be selected which will displace in excess of an additional 22.5 cu ft of water to assure positive buoyancy of the system. For purposes of calculations a 4-ft-diam flotation balloon was chosen providing a net positive buoyancy of 704 lb.

The finite velocity of the vehicle at water entry will cause submergence. If the depth of submergence is sufficient, water pressure may cause the collapse of the balloon. Flotation would not be achieved and the loss of the vehicle would result. It may be necessary to provide a scheme for inflation of the flotation balloon prior to water entry if the balloon cannot be inflated in the time interval available before it has been pulled to a "critical depth."

The vehicle A will have a terminal velocity of approx 12 fps in water without considering the effect of any aerial braking device which may have remained attached. Water depth penetration of the vehicle prior to reaching its terminal velocity (within 8 per cent) has been estimated and is presented in Table 1 for three separate water entry velocities. Also included in the table are the maximum g loads which would be encountered at water entry neglecting buoyancy and velocity decay during water penetration of the vehicle.

Where the flotation balloon is attached by a tether line to the vehicle and is fully inflated at the water surface at a time when the vehicle reaches its terminal velocity, the system will depress approximately an additional 3.5 ft before the momentum of the system is depleted.

If the balloon is inflated at a pressure of 3 psi above standard ambient sea level pressure for flotation, then the critical depth to which the balloon may be submerged before it will no longer provide positive buoyancy of the system is approximately 25 ft. If air is used as the inflating gas, 3.08 lb are needed.

The inflation of the balloon may be accomplished either prior to or subsequent to water entry. The advantage of

Table 1 Water entry characteristics for a hypothetical re-entry configuration weighing 4000 lb

Water entry velocity, fps	Water depth at terminal velocity, ft	g loads at entry
50	10.9	6
100	14.3	25
150	16.2	55

inflation prior to water entry is that, with a suitable length of tether line, the balloon may never necessarily be submerged and so suffer compression penalties and/or damage. If the balloon is inflated subsequent to water entry the problem of inflating the balloon while submerged may be somewhat offset by releasing the balloon from the vehicle with a length of tether line so that, initially, the balloon has only to raise itself to the surface. For a given set of conditions this line length may be determined such that the balloon has surfaced and is fully inflated by the time the tether line to the vehicle has drawn taut. If the balloon is to be subjected to unusual handling in connection with these problems, it may be reinforced by a suitable enclosure of nylon.

The balloon may be inflated, in general, by one of two methods; i.e., the inflation gas may be carried in compressed form in a suitable bottle or the gas may be generated chemically.

The disadvantages of the bottle method are the volume and weight penalties involved. If the 3.08 lb of air is compressed to 3000 psi, the volume is approximately that of a sphere 9 in. in diam and the total weight is in the order of 10 lb.

Hydrogen generators may be utilized, and, for the case of balloon inflation subsequent to water entry, hydrogen generators of compact size and capacity may be developed which utilize the characteristics of the combination of water (sea water, for example) with some, or one, of the active metals or their hydrides or borohydrides.

C Location Devices

Subsequent to impact, the location of the vehicle or component may be difficult. Described below are several of the currently considered devices which may be used either individually or simultaneously:

1 Bombs may be detonated upon impact, facilitating triangulation by seismic or sonar equipment.

2 A homing radio may be energized at the point and/or time of impact.

3 A balloon may be inflated and flown above the impact point. The balloon may carry a radar reflector with it to facilitate discovery.

4 Dye may be expelled at impact. For ground recovery this may be in the nature of a bomb which would splatter a sizable area, while for water recovery this may be a water soluble process.

5 A gas generator may be employed to send a plume of colored gas into the air for a period of time following the impact or at a prescribed interval of time following the impact.

Generally, for ground recovery conditions the marker devices may be jettisoned from the vehicle at some minimum altitude prior to the impact, while for water recovery conditions it would be advisable to leave the location devices attached to the vehicle if possible.

5 Braking Principles

The high speed rocket powered vehicle and/or its components may be retarded by employing devices which generally rely on the production of lift, drag, impulsive, or retrothrust forces. The selection of a particular recovery device is made on the basis of factors such as drag weight considerations and the operating range over which the recovery will be attempted. For example, the most favorable conditions of velocity are those which require a minimum reduction in velocity; in other words, the least possible vehicle speed at "initiation" of the brake and the maximum allowable impact velocity.

The fabric parachute has long been used as the mainstay of recovery systems because of its high drag-to-weight and bulk ratios and its general adaptability to diverse stowage requirements. Its use at Mach numbers exceeding two at medium or lower altitudes, however, is limited by the high temperatures encountered in these ranges. Unhappily, the heat transfer of nylon is negligible regardless of the mass of fabric used in the construction, and the temperature in the fabric, therefore, is that obtained from aerodynamic friction (3).

These factors require that temperature resistant versions of fabric parachutes and other braking principles be investigated and their characteristics evaluated in terms of efficiency and adaptability.

There are two broad categories of braking principles under which particular types naturally fall. These categories may be distinguished by the manner in which the braking devices are connected to the vehicle; that is, there are devices which are towed by, and devices which are rigidly fastened to, the vehicle.

Towed devices, such as parachutes, streamers, streamers with drag plates, are attached to the vehicle by lines or flexible cables. These systems are highly adaptable to packaging and facilitate stowage and attachment to the vehicle. A recovery system using the towing principle lends itself to considerable standardization and may be adapted to various vehicles with minor changes to itself and to the vehicle. It, however, introduces large "snatch" forces under high velocity, low altitude operation and requires detailed attention in design to assure orderly deployment. The experience gained in the high speed application of fabric parachutes, however, serves as a useful guide and the satisfactory procedures developed can be applied to towed braking devices of other than fabric construction.

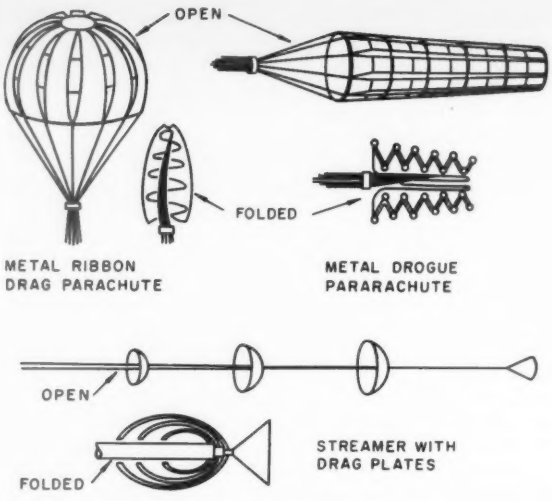
Rigidly attached devices in general require a greater degree of tailoring in order to be adapted to particular vehicles and require greater modification to the vehicle structure. Most of the devices in this category become effective when extended from the vehicle, and as such must be designed to withstand large bending moments and to minimize the forces required for actuation.

Since, in general, the actual operation of the various types of braking devices are expected to be utilized in the velocity range of $N_M \leq 5$, the following discussions are given with respect to this fact. For purposes of comparison, a value of 16 for C_DA has been used throughout the discussion.

A Parachutes or Drogues

The fabric parachute in its many forms is well known. Perhaps the most suitable of these for high velocity application where *intermediate stability* is satisfactory is the ribbon parachute. Fabric parachutes may be employed to surprisingly high Mach numbers at very high altitudes (as will be shown later) since under these conditions a low heat transfer coefficient and high radiation importantly reduce the maximum temperatures attained. At lower altitudes an upper limit of $N_M = 2.0$ seems to apply because of high temperatures. Parachutes made from temperature resistant materials, such as Fiberglas and metal, have been suggested as solutions to this temperature problem. It is also known that other high temperature materials are under investigation for possible use in parachutes.

Conventional Fiberglas has the disadvantage that it is considerably susceptible to fatigue failure. It is therefore doubtful that it can be used when folding and packing are required or when high rate flexing stowage or operation is encountered.



REPRESENTATIVE SYSTEM WEIGHTS	DRAG LOAD	
	100,000 LB	600,000 LB
PARACHUTE OR DROGUE	180 LB	250 LB
TELESCOPED STREAMER	120 LB	650 LB
CABLED STREAMER	140 LB	900 LB

Fig. 5 Some representative towed braking devices

Parachutes made of metal elements can sustain higher temperatures. Examples of a metal-type parachute and a drogue are shown in Fig. 5 in folded and inflated conditions.

High speed tests of fabric parachutes indicate that the drag coefficient is independent of Mach number. The drag coefficient based on inflated or frontal area is about 1.3. The drag coefficient of the drogue is also 1.3, and the same independence of Mach number is expected. Both these devices can be stabilized by using sufficient porosity. In the case of parachutes, a porosity of approximately 20 per cent is adequate for stability.

The major problem in the design of these devices for Mach No. 5 is maintaining packageability when using materials that can withstand high loads and high temperatures. Metal structures using steel bands as shown in Fig. 5, or chain-mail cloth can meet these requirements and still maintain some stowage flexibility. In applications to larger vehicles, the folding of the device may not be necessary.

The efficiency of these devices in terms of weight and bulk is of necessity lower. However, canopies would withstand a force of 590,000 lb (C_DA = 16 and N_M = 5.0 at sea level) if constructed of suitably reinforced 0.020-in. steel bands and would weigh approximately 20 lb. The size of steel cables required to transmit this load to the missile, however, becomes quite large as shown in Fig. 5. The problems of packaging such heavy cabling are, of course, obvious.

B Streamers with Drag Plates

The type of device referred to at this point is shown in extended and folded arrangement in Fig. 5. The drag plates are added to the streamer or cable since, without these, excessive cable lengths would be required. For example, a cable with an average diameter of 1 in. would have to be 2500 ft and would weigh 4500 lb to produce a drag area of 16 sq ft.

By attaching drag plates as shown in Fig. 5, the cable is greatly shortened, and large drag coefficient per unit frontal area can be developed. The plates, cup- or wedge-shaped to increase drag, are spaced eight diameters apart to reduce mutual interference and wake effects. The succeeding plates along the cable are progressively increased in diameter to favor air capture. The drag coefficient of each plate based on its area at supersonic Mach numbers approaches the theoretical maximum drag obtainable; that is, $C_D \backsimeq 1.8$. Thus, 16 sq ft of drag area can be obtained with a cable that is 50 ft long and has three sets of drag plates attached to it.

The cone attached at the end of the cable is employed to stabilize the cable by producing a restoring lift proportional to the angle between the cable axis and the relative air stream.

Packaging and adaptability of this system are similar to that of the parachute.

C Retro-Rockets

Retro-rockets, that is, rockets mounted so that the thrust is directed into the direction of motion, have successfully been employed to decelerate track-borne vehicles. The weight of propellant required to decelerate an airborne vehicle from N_M = 5.0, however, is excessive. For example, 7000 lb of propellant with a specific impulse of 180 sec is necessary to decelerate a 10,000-lb missile from N_M = 5.0 to N_M = 1.0. Clearly, this type of braking is of remote usefulness for such applications. The systems which rely upon aerodynamically generated forces appear to have greater possibilities.

D Rotochutes

The rotochute is a device which is similar in operation to the autorotating helicopter rotor. It has been successfully used to recover small stores released at low speeds. It appears to be capable of recovering loads up to at least 1000 lb and at speeds corresponding to N_M = 1.0. It has very high stability characteristics.

At subsonic speeds, the retarding thrust or equivalent drag that the rotochute produces is comparable to that of a parachute with an inflated area equal to the disk area of the rotochute. Its effectiveness at supersonic speeds is virtually unknown. However, it is expected that the effectiveness will be substantially reduced as has been found to be the case in low supersonic Mach number tests of propellers.

The rotochute is most conveniently attached to the nose or the base of the vehicle. A typical installation is shown in Fig. 6.

The type of rotochute that might be considered for this application would have a blade pitch control actuated automatically by the air load on the blade. The pitch control

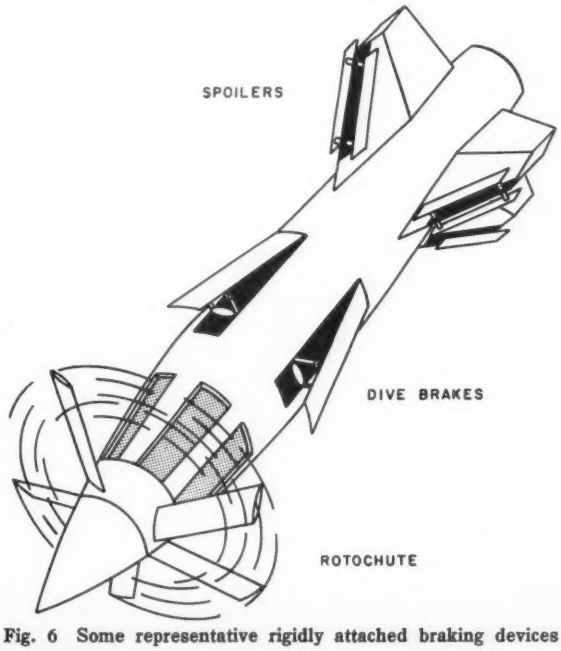


Fig. 6 Some representative rigidly attached braking devices

would be necessary to prevent excessive rotational speed at high velocity. The pitch control has the further advantage that it tends to maintain a constant drag force vs. velocity rather than a force which varies with the square of the velocity. It thus incorporates the characteristics of continuous disreefing of parachutes.

The major disadvantages of the rotochute, aside from the mechanical problems of designing suitable thrust bearings, are its limited adaptability and large bending moments in the rotor blades.

In most instances the nose section of a vehicle contains instrumentation or equipment which cannot conveniently be interfered with. If the rotochute were mounted at the tail of the vehicle, it would have to be mounted near the center of the wake so that pulsating forces applied to the blades by their passage from the wake to relatively undisturbed flow conditions would be minimized. Such an arrangement is undesirable from two standpoints: (a) This is the area that is usually reserved for the power plant, and (b) the rotochute blade would have to be increased in span in order to compensate for the loss in effectiveness due to operation partially in the wake of the vehicle.

The large bending moments applied to the blades can be reduced by increasing the number of blades. However, the span of the blades or disk area cannot be reduced since it is disk area rather than blade area that determines the effectiveness of propellor types of devices. Thus, by using a larger number of blades, the drag per unit weight of the rotochute is reduced. In spite of these shortcomings, the rotochute has several desirable characteristics which make it worthy of continued development and study.

E Spoilers and Dive Brakes

In many respects spoilers and dive brakes are similar and it is somewhat difficult to distinguish one from the other. In this discussion, the terms are used somewhat loosely. Devices which are extended primarily by rotation about some axis are named dive brakes, while those that are extended primarily by translation are termed spoilers. Fig. 6 displays possible spoiler and dive brake arrangements.

Slat-type spoilers are also shown in Fig. 6. When retracted, these are flush with the profile of the fins to which they are attached. Extension is accomplished by permitting air to enter at the leading edge of the slats at the desired time causing an internal pressure which forces the slats to extend. The effect of the extended slats is to establish a detached shock wave in front of the fins, thereby greatly increasing their drag. In the supersonic range of Mach numbers, the drag of such spoiler slats is approximately 1.6; thus the required frontal area is 10 sq ft.

In some instances it may be possible to detach or blunt the nose of a vehicle at a predetermined time, thus increasing its drag coefficient. The rise in drag coefficient is caused by shock and an accompanying increase in entropy across the shock wave. Nose blunting is an effective device for the larger diameter vehicles, since such vehicles provide the greater area available for blunting. The aerodynamic effectiveness of nose blunting decreases with Mach number, i.e., for the same percentage of bluntness a larger vehicle area is required to produce a drag area of 16 sq ft at the lower Mach numbers (4).

Spoilers are basically rugged structures and are capable of withstanding very high loads and temperatures which are at least as high as those that the vehicle can withstand. The actuating forces required are relatively low since extension can be accomplished by translation in a direction normal to the air stream, or the aerodynamic forces themselves can be used to extend them.

The major disadvantage is adaptability. It is doubtful that a spoiler system could be developed which would apply to all vehicles since its type and location must be compatible with the structure, stability, and configuration of the vehicle.

Dive brakes have been used for many years on aircraft. Considerable data exist on various types of perforated brakes. The dive brakes shown in Fig. 6 extend by rotating about a rearward hinge line to eliminate hinge moments that would be encountered with a forward hinge line. Dive brakes provide a greater degree of flexibility in selecting a location on the vehicle. Since they must extend farther into the air stream, they are less rugged structurally than spoilers.

F Impulse Devices

Impulse devices rely on a deflection of the air stream by curved turbine-like buckets. The drag devices that have been discussed in the foregoing sections are capable of delivering retarding forces per unit frontal area equal to or, in most cases, greater than the impulse techniques. It therefore does not appear that the impulse devices offer any improvement over other types and it is unlikely that any advantage could be obtained in their application.

With the exception of retro-rocket and possibly impulse devices, the braking devices described offer sufficient promise that further exploration of their use is warranted. The listing given above is presented primarily to attempt a greater definition of possibilities and is not intended to be complete.

6 Thermal Effects

Fig. 7 shows the variation of equilibrium temperature with altitude over a range of Mach numbers for a disk with a drag area of 16 sq ft. A disk or flat plate normal to the air stream is used for this illustration because this configuration would apply to parachute-shaped, trailing disk, rotating vane, and spoiler or dive-brake type drag devices. From the curves it is seen that the equilibrium temperatures are greatest at high Mach numbers and low altitudes. However, it is not reasonable that sustained flight at high speeds would be carried out at these altitudes, and therefore the equilibrium temperature may never be attained. At altitudes above 150,000 ft the equilibrium temperature drops progressively.

From Fig. 7 it may be concluded that at high altitudes reasonable temperatures may be maintained if the time of flight is kept low at $N_M \leq 5.0$. Below 100,000 ft the possi-

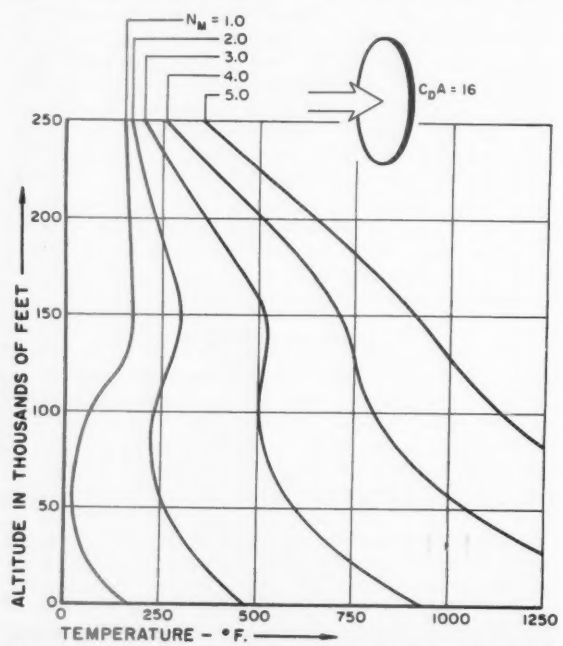


Fig. 7 The variation of equilibrium temperature with altitude for several constant values of Mach number

bility of excessive temperature at $N_M \geq 4$ increases. However, with the higher air density encountered at these low altitudes the drags realized will be higher and the deceleration of the vehicle will be greater, which means less flight time at the higher Mach numbers.

It should be remembered that the equilibrium temperatures could be attained only after an extended time of exposure to the heating conditions. For a vehicle with a drag device operating the trajectory would be a steepening path and the altitude would reduce rapidly. The equilibrium temperature at a given altitude is therefore not attained since the vehicle passes rapidly through the changing temperature levels.

In the case of low altitude, high velocity flight the equilibrium temperatures are again not attained, since, under these conditions, the decelerations to low Mach numbers are so rapid that the equilibrium temperatures that would exist at the high velocities do not have time to develop.

In order to show the effects of heating at high speeds, another hypothetical case is considered for a 10,000-lb reentry-type vehicle incorporating a drag device of 16 sq ft drag area. For this example it was assumed that the missile was falling vertically at a $N_M = 5.0$ and that the drag device was deployed at an altitude of 250,000 ft. Fig. 8 shows the history of the fall from 250,000 ft to sea level. Shown are velocity, Mach number, acceleration, time, and temperature vs. altitude.

The temperature history of the drag device was calculated assuming the material used to be 0.04-in.-thick steel. This thickness of material is greater by a factor of two than that which would be required from a purely structural loading standpoint for metal parachute canopies and similar devices. From the figure it is seen that temperatures exceeding 1000 F occur after 31 sec of fall or at an altitude 80,000 ft. The reasons for these extreme temperatures are:

1 The low drag of the device at high altitude allows the vehicles to accelerate to a $N_M \backsimeq 6.0$ before beginning to slow down.

2 The boundary layer temperature increases due to both the velocity and the ambient air temperature.

3 The heat transfer increases due to increasing air density.

4 The material thickness (0.040 in.) is incapable of storing the large quantities of heat transferred to it except through a rapid rise in its temperature.

Beyond 36 sec the temperatures drop due to the reduction of speed under the decelerating influence of the increasing drag load.

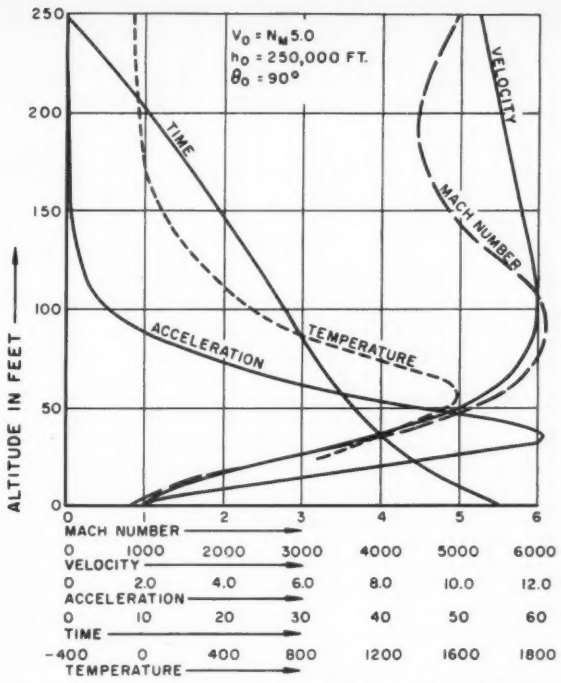


Fig. 8 Trajectory history of a 10,000-lb vehicle with a 16 sq ft drag area braking device, illustrating the temperature rise

It is to be noted that such extreme temperatures would not be encountered in the case of lower weight vehicles since significant decelerations due to a 16 sq ft drag area would become effective at higher altitudes. The maximum temperatures obtained would also be reduced if thicker members were employed, such as would be necessary in the case of spoilers and dive brakes. However, substantial reduction of peak temperatures, by adding material beyond the point of structural needs, reduces the drag-to-weight ratio; and other methods of controlling the temperatures, such as cooling, are more desirable. The use of transpirational cooling appears to be especially desirable for these applications and its utilization is being explored.

(Continued on page 147)

Table 2 Summary of major characteristics of some braking devices

Device	C_D (based on exposed frontal area)	Drag-weight[1] ratio	Advantages	Disadvantages
Parachute (metal)	1.25	1300	permits greater standardization in package form	large snatch forces, important temperature problems
Streamer with drag plates	1.7 (per plate)	715 (cable suspension)	simplifies packing, can be standardized, reduces snatch forces	less efficient than parachute, important temperature problems
Retrorockets	not applicable	not applicable	some possibility of control	inadequate
Rotochute	design is capable of producing a drag coefficient that varies somewhat like V^{-1}		desirable drag velocity variation, high stability	large bending moments, large initial actuating moments required; location limited to nose and tail areas of fuselage or to leading or trailing edges of fins
Spoilers	1.6	greater than dive brakes	rugged structure, facilitate actuation	possible location restricted by missil configuration and size, less susceptibility to standardization
Dive brakes	1.6	900	suitable to varied missile locations	similar to spoilers but less restrictive, capable of greater standardization
Impulse	less than spoilers or dive brakes	less than spoilers or dive brakes	none	spoilers and dive brakes appear superior for most applications

[1] Drag-weight ratios are based on a 100,000-lb drag load and the structural weight required to support this load. The weight of the structural reinforcement of missile parts to sustain the load are not included.

Heat Transfer to Satellite Vehicles Re-entering the Atmosphere

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A recently developed theory of heat transfer at high velocities and high altitudes is applied to the problem of a satellite vehicle entering the atmosphere. Circular re-entry orbits are considered for bodies under the influence of gravity and drag forces. Numerical results are presented which can be used to determine the conditions under which the survival of such a satellite may be expected. In addition, an analysis is made of the value of exerting a lift force on the re-entering vehicle as a means of preventing its destruction.

Nomenclature

a = body surface area
A = area on which drag coefficient is based
C_L = lift coefficient $C_L = L(1/2)\rho u^2 S$
C_D = drag coefficient $C_D = D(1/2)\rho u^2 A$
C_p = specific heat at constant pressure per unit mass
c = scale height of atmosphere, Equation [B8]
D = drag
g_0 = acceleration of gravity at earth's surface
H = altitude
h_D = average atomic dissociation energy times atom mass fraction
h = enthalpy per unit mass
K = $20{,}800/\sqrt{\rho_0}\, u_c^{3.25} \sqrt{R}$
L = lift in Appendix B; Lewis number in Appendix A
M = body mass
q = heat transfer rate per unit area and time
r = distance from center of the earth
R = nose radius of body in a meridional plane
S = area on which lift coefficient is based
T = temperature
t = time
u = flight velocity
u_1 = velocity at the edge of the boundary layer
u_c = circular velocity, Equation [B2] (taken as 26,000 fps in numerical calculations)
W = body weight
x = coordinate along body surface from stagnation point
α = Stefan-Boltzmann constant
ρ = mass density
μ = viscosity
ϵ = surface emissivity
η = accommodation coefficient in free molecule flow, Equation [2]
σ = Prandtl number

Subscripts

1 = edge of boundary layer
w = body surface
s = stagnation point
0 = surface of the earth
R = radiated

Presented at the ARS 11th Annual Meeting, New York, N. Y., Nov. 26–29, 1956.

[1] Senior Scientist.

[2] Principal Research Scientist.

[3] Numbers in parentheses indicate References at end of paper.

Introduction

IN OUR progress toward making space flight a reality, safe re-entry into the atmosphere is now recognized as one of the most serious problems. This view was, for example, expressed by several members of the AMERICAN ROCKET SOCIETY at the symposium on earth satellites held at the Franklin Institute in April 1956.

The re-entry problem has been examined previously by several authors (1, 2, 3).[3] All this work has been hampered to some degree, however, by lack of an aerodynamic theory that adequately treats the very high flight speeds that must be considered. One purpose of this paper is to direct attention toward recent theoretical work that has been done in this field at the Avco Research Laboratory. In particular, a heat transfer theory has been developed which we believe may be used with some confidence for velocities up to the satellite velocity and at altitudes up to the extreme limit of the continuum flow regime. Combining this with the limiting values of heat transfer that occur in the free molecule flow at very high altitudes allows a fairly accurate calculation of the heat transfer to a satellite entering the atmosphere.

A body travelling at the satellite velocity possesses a tremendous amount of kinetic energy. In fact, a third of this energy if converted into heat in the body is sufficient to vaporize the body completely, regardless of its construction. The major initial problem to be faced in bringing the satellite safely to earth through the atmosphere is to dissipate this energy while converting only a small fraction into residual heat in the body. We wish to examine here how this might be done by purely aerodynamic means. In so doing, we hope to establish some basic information which will be useful in evaluating more specific proposals, i.e., decelerating rockets, deceleration by skipping, etc. In addition, examining the basic nature of the problem may point to less conventional methods of solution.

Heat Transfer Theory for Continuum Flow

The major new phenomena that requires consideration in developing an aerodynamic theory for very high speed flight in continuum flow is the fact that the compression of the gas in the shock wave preceding the body can raise its temperature to several thousand degrees Rankine and thus cause dissociation and ionization of the air molecules. At the nose of a body travelling at the satellite velocity at high altitudes where the gas is brought to rest, more than half its internal energy will go into dissociating the molecules. Lees in a recent issue of JET PROPULSION (4) has examined this problem and proposed an approximate method for computing heat transfer under these conditions. Concurrently, a more detailed examination of the problem has been made at the Avco Research Laboratory (5). We have accepted the fact that a blunt nose is essential for high speed flight, and have therefore investigated the boundary layer at the stagnation point of a blunt body. It turns out this problem can be for-

mulated exactly, even including dissociation phenomena, within the bounds of a similarity theory. The resulting equations were solved numerically on a digital computer. The accuracy of the results is limited mainly by the present inadequate knowledge of the transport properties of high temperature air. A correlation of the numerical results was then made which produced the following simple formula for computing the heat transfer rates at the stagnation point

$$q_s = \frac{20{,}800}{\sqrt{R}} \sqrt{\frac{\rho}{\rho_0}} \left(\frac{u}{u_c}\right)^{3.25} \left(1 - \frac{h_{ws}}{h_{s1}}\right) \text{Btu/ft}^2\text{-sec} \quad \ldots [1]$$

The method of establishing this empirical formula and a comparison with other theories is given in Appendix A. It should be emphasized that Equation [1] is not an exact expression of the theoretical results but is a convenient approximate formula for our present purposes.

The details of the theoretical investigation are given in (5) and need not be discussed here. It is worth noting, however, that the state of the boundary layer is strongly dependent upon whether the dissociated atoms which exist in the free stream do or do not recombine as they diffuse through the boundary layer. A theoretical investigation of this problem was also made in (5) and it was determined that, provided the solid surface acts as a catalyst for the atom recombination, the heat transfer is not changed appreciably by this nonequilibrium phenomena. This point is important, since it is almost certain that at the high velocities and altitudes of interest the boundary layer will, in fact, be in a nonequilibrium state. Thus Equation [1] can be used in general for continuum flow over catalytic surfaces though it is developed under the assumption of thermal equilibrium.

In the analysis given below it has been assumed that the body surface is catalytic. It should be pointed out that according to the results of (5) use of a noncatalytic surface could theoretically reduce the heat transfer rate by a factor of two or more at high velocities and altitudes. This possibility has not yet been investigated fully.

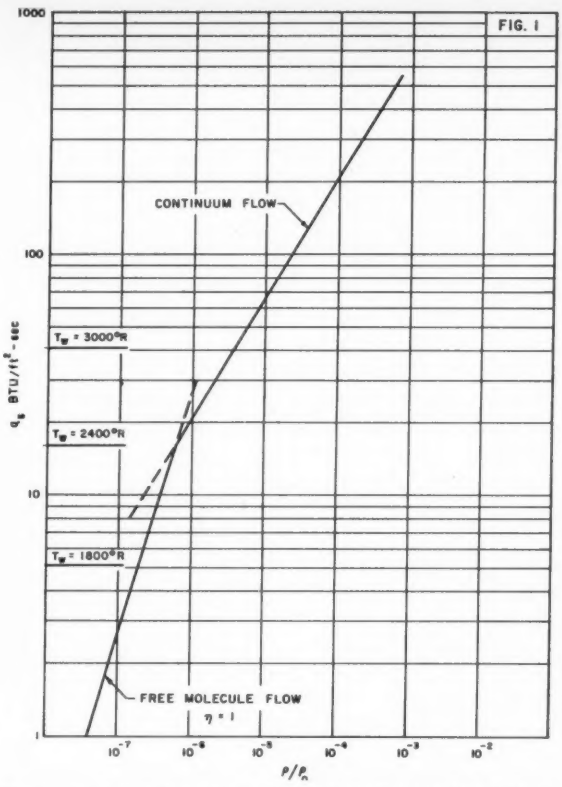

Fig. 1 Heat transfer rate q_s at the stagnation point of a blunt body of 1-ft nose radius travelling at a satellite velocity of 26,000 fps, as a function of air density ratio ρ/ρ_0; T_w is surface temperature of a surface with emissivity $\epsilon = 1$, which radiates heat at the rate q_s

Heat Transfer for Satellite Re-Entry

When a satellite first re-enters the atmosphere it is in a region of free molecule flow where the stagnation point heat transfer may be described by

$$q_s = 2.69 \times 10^7 \, \eta \, \frac{\rho}{\rho_0} \left(\frac{u}{u_c}\right)^3 \text{Btu/ft}^2\text{-sec} \quad \ldots [2]$$

where η is the accommodation coefficient based on energy transfer. The accommodation coefficient is not known in general but it certainly has an upper limit of unity; i.e., when $\eta = 1$ all the kinetic energy of the incident molecules is transferred to the body. As the re-entering body descends lower into the atmosphere, the mean free path decreases and the flow eventually becomes of the continuum type, i.e., the usual high speed aerodynamic flow with attendant shock wave and boundary layer phenomena. The transition region between free molecule flow and continuum flow is known as the slip flow regime.

To show the interesting heat transfer regions, we have plotted in Fig. 1 the stagnation point heat transfer rate to a body travelling at satellite velocity as a function of air density. In addition, the rate at which heat is radiated is shown for several surface temperatures (the emissivity is assumed to be unity). The effect of slip flow must be to cause a gradual transition from the continuum to the free molecule heat transfer rate. In order to simplify the present analysis we have considered the slip flow heat transfer rates to be sufficiently well represented by extrapolating the continuum flow results up to the free molecule region as indicated in the figure.

It is of interest also to note how the kinetic energy of the re-entering vehicle is dissipated aerodynamically. The rate at which energy is dissipated is given by the drag of the body times its velocity. What we wish to examine is how much of this dissipated energy is actually transferred to the body. The maximum rate at which heat can be transferred to the body is one half the rate at which energy is dissipated by drag. Fig. 2 shows the variation with altitude of the ratio of the rate at which heat is actually added to the body to this maximum possible rate. In the continuum flow regime where q_s is given by Equation [1], this ratio varies inversely as the square root of the density, while in the free molecule region, with q_s from Equation [2], it is given by the value of the accommodation coefficient.

Figs. 1 and 2 allow a general assessment of the heating problem to be faced if we are to decelerate the incoming vehicle by aerodynamic means. From the point of view of minimizing the time integrated heat input to the body we would conclude from Fig. 2 that it is most advantageous to decelerate at low altitudes. On the other hand the heat transfer rates would be very high in this case and it would become difficult to meet reasonable surface temperature requirements. Furthermore it appears that if the first satellites are successful (i.e., if they complete very many circuits of the earth outside the atmosphere), they will probably assume nearly circular orbits in the outer fringes of the atmosphere and hence will enter the important heat transfer regions on a tangential path. A device such as auxiliary rockets would then have to be used, as suggested by Porter (3), if we wish to get them into the lower atmosphere quickly.

An alternative scheme is to decelerate at altitudes high enough so that the heat input rate can be balanced by heat radiated from the body. This requires deceleration at very high altitudes if presently acceptable surface temperature requirements are to be met (see Fig. 1). In this case a large

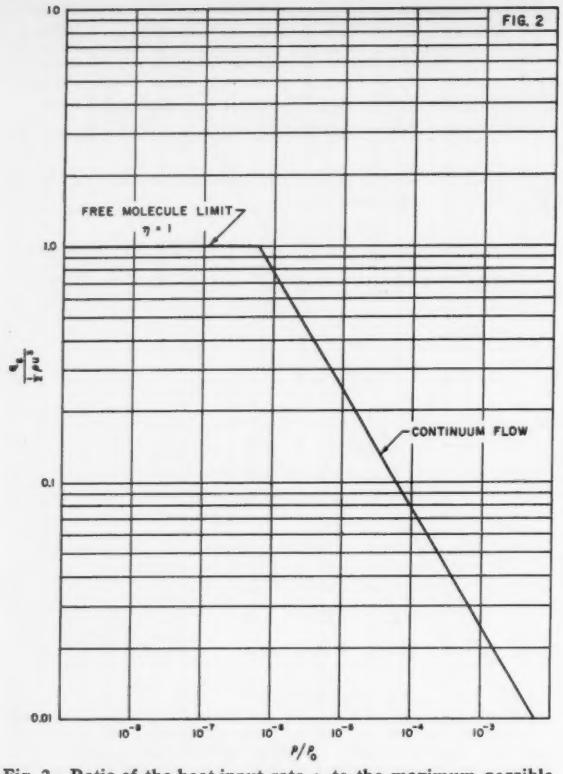

Fig. 2 Ratio of the heat input rate q_s to the maximum possible heat input rate $\frac{1}{2}\rho u^3$ as a function of air density ratio ρ/ρ_0; evaluated at the stagnation point of a blunt body of 1-ft nose radius travelling at a satellite velocity of 26,000 fps

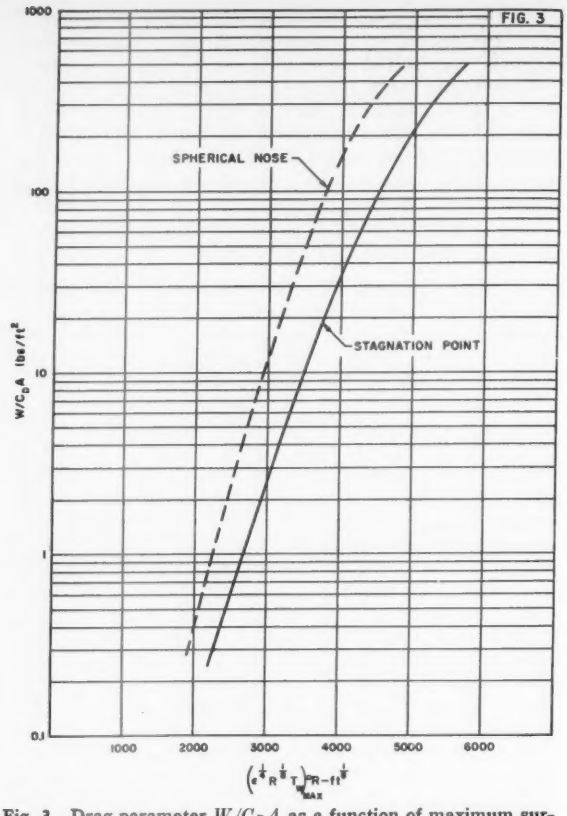

Fig. 3 Drag parameter W/C_DA as a function of maximum surface temperature parameter $(\epsilon^{1/4}R^{1/8}T_w)_{max}$ for simple drag body

percentage of the energy to be dissipated will be transferred to the body, though at a slow rate. Of course, this energy is at the same time being radiated away, at the same rate. Two things seem certain if we adopt the idea of high altitude deceleration: First, the deceleration will take a relatively long time since a large amount of energy must be radiated at a low rate. Second, the amount of energy involved is so large that the heat sink capabilities of the body are negligible.

We have chosen in this paper to examine the case of deceleration at high altitudes. Before coming to the numerical results, however, a further point needs discussion. So far, only stagnation point heat transfer rates have been considered. Lees (4) has proposed a method of computing the ratio of the laminar heat transfer at a given point on a blunt body to the stagnation point value. It turns out for high velocities this ratio is essentially a function of the shape of the body only. Hence the heat transfer to the body can be given as a constant times the stagnation point value. This is a great simplification and is probably valid for blunt bodies without any sharp corners. The other question that arises is whether or not the boundary layer will become turbulent away from the stagnation point. It appears in considering high altitude decelerations that the Reynolds number is so low that the boundary layer is almost certainly laminar everywhere on the body.

Body With Drag Only

Consider the case of a satellite re-entering the atmosphere tangentially from a circular orbit. The trajectory of such a body with drag alone has been computed several times before. The method used here was to compute the satellite orbit, with drag, analytically, until the nonlinear terms become important and then complete the computation on a digital computer. The atmospheric model presented in the Navord tables (6) was used. The heat transfer rate was computed according to Equations [1] or [2] and equated to the radiated heat transfer rate

$$q_R = \epsilon\sigma T^4 = q_s \quad \ldots\ldots\ldots\ldots\ldots\ldots [3]$$

where ϵ is the surface emissivity and α is the Stefan-Boltzmann constant, 0.476×10^{-12} Btu/ft²-sec-(°R)⁴. Results are shown in Fig. 3 where the ballistic drag parameter (W/C_DA) is plotted against the maximum value of the surface temperature parameter $\epsilon^{1/4}\ R^{1/8}\ T_w$. Since the emissivity ϵ is of the order one and the nose radius R (in feet) occurs to the $^1/_8$ power, this surface temperature parameter may read directly as maximum surface temperature for all practical purposes. The solid curve is based on stagnation point heat transfer rates.

This calculation can be modified for different shapes by considering the ratio of the total heat input rate to the body to the stagnation point rate as noted above. If the heat transfer rate at any point is given by q, then the heat rate for the whole body is $\int q da$. Assuming the whole body to radiate at a uniform temperature with rate q_R, the equilibrium equation is

$$q_R a = \int q da$$

or

$$q_R = q_s \int \frac{q}{q_s}\frac{da}{a} \quad \ldots\ldots\ldots\ldots\ldots\ldots [4]$$

Comparison with Equation [3] shows that taking account of the whole body involves the factor $\int (q/q_s a)da$. An approximate expression for q/q_s for spheres is given by Lees (4, Equation 15). When this expression is used, on the front half of a sphere, the value of the integral varies from

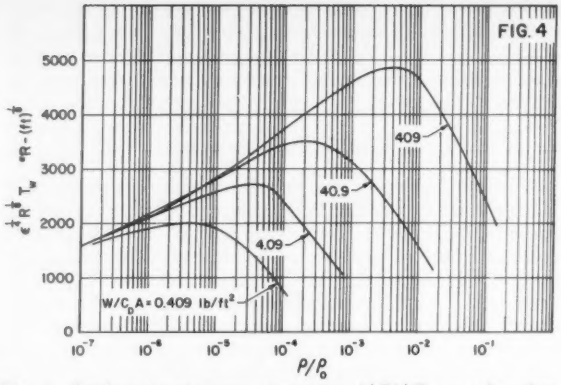

Fig. 4 Surface temperature parameter $\epsilon^{1/4}R^{1/8}T_w$ as a function of air density ratio ρ/ρ_0 for several values of the drag parameter W/C_DA; simple drag bodies

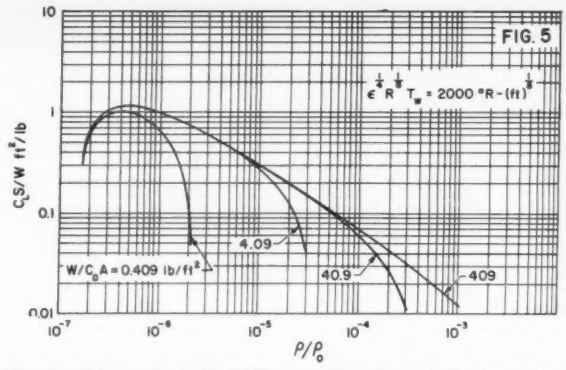

Fig. 5 Lift parameter C_LS/W as a function of air density ratio ρ/ρ_0 for several values of the drag parameter W/C_DA; constant heat transfer trajectories with surface temperature parameter $\epsilon^{1/4}R^{1/8}T_w = 2000°\text{R} - \text{ft}^{1/8}$

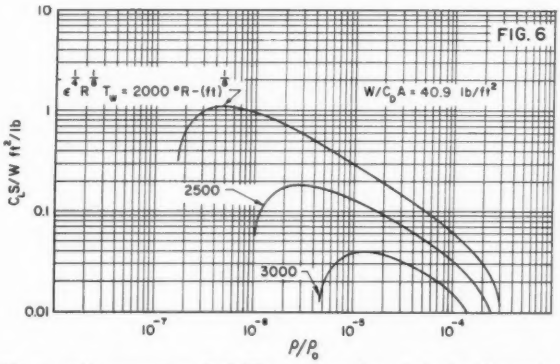

Fig. 6 Lift parameter C_LS/W as a function of air density ratio for several values of the surface temperature parameter $\epsilon^{1/4}R^{1/8}T_w$; constant heat transfer trajectories with drag parameter $W/C_DA = 40.9$ lb/ft²

0.4 to 0.5 depending on flight speed and altitudes, being close to 0.5 for Mach numbers above 10. The dotted curve in Fig. 3 was obtained from the solid curve by applying the factor 0.5 to the stagnation point heat transfer rate before computing the temperature. This factor might be modified slightly if we consider using the back of the sphere as a radiating surface also. The problem of transporting the heat in the body complicates this consideration, however, and it appears that the possible further gains are much less than the factor obtained by considering the nose alone.

Fig. 4 shows the surface temperature reached on the nose of spherical satellites with different values of W/C_DA as a function of air density. It should be noted that the maxima, which have already been plotted in Fig. 3, occur in or very near to the continuum flow regime. For the proposed Vanguard satellite ($W/C_DA \lesssim 10$) it can be seen that destruction will occur at a high altitude.

These results show that for a reasonable maximum surface temperature, say 2500 R, the value of the drag parameter necessary for safe re-entry is very low. It is difficult to see how a body could be constructed that would have W/C_DA less than 2 lb/ft² and still stand a 2500 R surface temperature, these being the apparent requirements for safe re-entry of a simple drag body. One is led at once to consider, therefore, whether this situation may be improved by providing a lift force so that the body may stay at high altitudes for a longer period of time and thus enter the denser atmosphere at lower velocities.

Constant Heat Transfer Trajectories

The problem of providing lift has been examined from the following point of view, which leads to a simple but informative analysis. For a given surface temperature the radiated heat rate can be computed. Using the heat transfer theory, a velocity-density relationship can then be determined such that the heat input to the body is exactly equal to the radiated heat output. These constant heat transfer trajectories represent the fastest deceleration that can be achieved without exceeding a fixed surface temperature. It is, of course, necessary to exert lift forces to traverse such trajectories. One can find, for a given value of the drag parameter W/C_DA, what values of the lift parameter C_LS/W are required. The method of analysis is given in Appendix B, where it is shown that C_LS/W is given by

$$\frac{C_LS}{W} = \frac{1-(u/u_c)^2}{\frac{1}{2}\rho u^2} - \frac{g_0 c}{2}\left(\frac{C_DA}{W}\right)^2 \rho\left(1-\frac{2h_{sw}}{u^2}\right)^{-2} \times 35.75\left\{1 - 0.234\,\frac{4h_{sw}}{u^2} + 0.105\,\frac{8h_{sw}^2}{u^4}\right\} \quad \ldots [5]$$

where c is the scale height of the atmosphere in the important heating region. From Equation [1] air density can be written as a function of flight velocity u

$$\rho = \left(\frac{q_s}{K}\right)^2 u^{-6.5}\left(1-\frac{2h_{sw}}{u^2}\right)^{-2} \quad \ldots [6]$$

where K is the constant $20{,}800/\sqrt{\rho_0}\,u_c^{3.25}\sqrt{R}$.

For a given drag parameter and heat transfer rate, Equations [5, 6] permit C_LS/W to be found as a function of either u or ρ, thus determining how the lift has to be exerted as a function of altitude in order to stay on a trajectory which yields the chosen constant value of q_s. As a function of either ρ or u, starting at the circular velocity u_c and a high altitude (low density), C_LS/W begins at a negative value but immediately becomes positive, reaching a maximum, and then decreasing again to negative values as u approaches zero. The value of $(C_LS/W)_{max}$ could be found analytically, but the algebraic complications are such that it is more convenient to trace the trajectory on a computing machine and pick out the maximum.

In the calculations using Equation [5], the scale height c was taken as 35,000 ft, $\rho_0 = 0.002378$ slug/ft³ and $u_c = 26{,}000$ fps. The surface enthalpy h_{sw}, which contributes only small corrections, was found from

$$h_{sw} = C_pT_w$$

where C_p was taken appropriate to T_w. The surface temperature for finding h_{sw} was found by equating the given q_s to the heat radiated at T_w by

$$q_s\sqrt{R} = q_R\sqrt{R} = \epsilon\alpha T^4\sqrt{R} \quad \ldots [7]$$

using $\epsilon = 1$ and $R = 1$ ft.

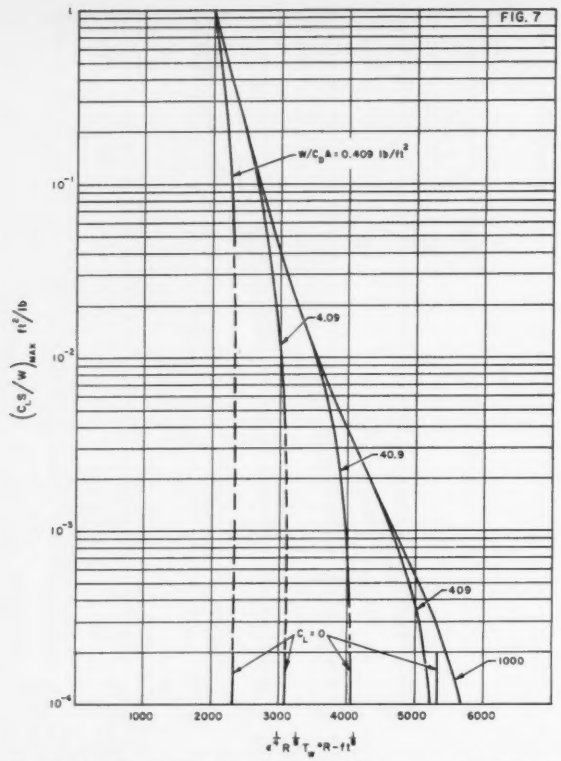

Fig. 7 Maximum lift parameter $(C_LS/W)_{max}$ as a function of surface temperature parameter $\epsilon^{1/4}R^{1/8}T_w$ for several values of the drag parameter W/C_DA; constant heat transfer trajectories; lines at bottom marked $C_L = 0$, show values of $\epsilon^{1/4}R^{1/8}T_w$ at which the lift parameter is zero

The results of these calculations are given in Figs. 5, 6, and 7 in terms of the lift parameter C_LS/W, the drag parameter W/C_DA, and the surface temperature parameter $\epsilon^{1/4}R^{1/8}T_w$. Stagnation point heat transfer rates were used throughout these calculations. A correlation factor for a specific body shape may be applied as discussed above. For example, for a spherical nose with a heat distribution mechanism the surface temperature parameter should be reduced by multiplying by $(0.5)^{1/4}$.

Figs. 5 and 6 show the variation of the lift parameter with density along a constant heat transfer trajectory. Fig. 5 shows that for the given value of the surface temperature parameter the position and value of $(C_LS/W)_{max}$ is essentially independent of W/C_DA over a range of W/C_DA values which depend on the surface temperature parameter (see Fig. 7). On the other hand, Fig. 6 shows that as the surface temperature parameter is increased the value of $(C_LS/W)_{max}$ is reduced sharply and moved to lower altitudes.

The effect of lift is most clearly shown by cross plotting $(C_LS/W)_{max}$ from data such as is shown in Figs. 5 and 6. This has been done in Fig. 7. The asymptotic values indicated at the bottom of the figure are the maximum values of the surface temperature parameter reached at the stagnation point of a body without lift (from Fig. 3). The striking feature of Fig. 7 is the large range of values of $(C_LS/W)_{max}$ over which lift is completely ineffective in reducing surface temperature for a given W/C_DA. However, if $(C_LS/W)_{max}$ is increased sufficiently this behavior changes and lift does become effective in reducing surface temperature. Eventually a value of $(C_LS/W)_{max}$ is reached where the given W/C_DA curve merges with the curves for all higher W/C_DA values, and hence the surface temperature parameter is then controlled by lift alone for this range of W/C_DA. This is the behavior illustrated in Fig. 5.

Reasonable maximum values of C_LS/W obtained by extrapolating from current aerodynamic practice fall in the range 0.02 to 0.05. It would appear, then, that for light, high-drag bodies (say W/C_DA less than 10 lb/ft²) it may be difficult to obtain sufficient lift by aerodynamic means to reduce substantially the surface temperature parameter.

Concluding Remarks

A major purpose of the analysis presented in this paper is to try to determine how effort should be directed in order to solve the problem of recovering a satellite. If a design is needed immediately then we must try to engineer a solution within the bounds implied by the above analysis. Almost certainly designs can be made which will meet the heating requirements for a safe re-entry. Clearly the difficulty of achieving such designs will depend to a large extent on the ability to make light structures that will stand a high surface temperature.

From a longer range point of view, however, we should try to increase our basic knowledge in directions that will ease this design problem. In this regard the following lines of investigation could be fruitful:

1 The possible use of noncatalytic surfaces to reduce the heat transfer rates in continuum flow at low densities.

2 A study of surface properties to try to obtain low values of the accommodation coefficient and thus reduce the heat transfer in the free molecule and slip flow regions.

3 The possibility of using unconventional means of generating lift at high altitudes, i.e., other than by the use of wings and without the weight penalties associated with the use of rockets.

APPENDIX A

Stagnation Point Heat Transfer Rates in Continuum Flow

The heat transfer calculations used in this paper are based on the formula given in (5, Equation 59).

$$q_s = 0.94 \left(1 - \frac{h_{sw}}{h_{s1}}\right) (\rho_{ws}\mu_{ws})^{0.1} (\rho_{s1}\mu_{s1})^{0.4} h_{s1} \sqrt{\left(\frac{du_1}{dx}\right)_s} \left[1 + 0.45(L-1)\frac{h_{D1}}{h_{s1}}\right] \ldots [A1]$$

This result was obtained from numerical solution of the stagnation point boundary layer differential equations using the properties of high temperature air in dissociation equilibrium from the National Bureau of Standards data (8). The viscosity μ was calculated by extrapolating Sutherland's law; the Prandtl number σ was held constant at 0.71; and the Lewis number L was taken as a constant. Calculations were made for $L = 1.0$, 1.4, and 2.0. For computing heat transfer rates in the present analysis, $L = 1.4$ has been used. The choice of these values for the transport properties is discussed fully in (5).

Some of the recent work on heat transfer to satellite vehicles (2, 3) is based on the work of Sibulkin (7). His result may be written in the present notation as

$$q_s = 0.763\, \sigma^{0.4} \left(1 - \frac{T_{ws}}{T_{s1}}\right) \sqrt{\rho_{s1}\mu_{s1}} \frac{C_p T_{s1}}{\sigma} \sqrt{\left(\frac{du_1}{dx}\right)_s} \ldots [A2]$$

To compare this with Equation [A1] we note that the constant $0.763\ \sigma^{-0.6}$ is very nearly equal to 0.94 for $\sigma = 0.71$. Further, for high velocities where dissociation becomes important one may argue that enthalpy gradients rather than temperature gradients determine the energy transfer. Therefore, the temperature ratio should be replaced by an enthalpy ratio and C_pT_{s1} should be interpreted as stagnation enthalpy. The difference between [A2] and [A1] is then a factor.

$$\left(\frac{\rho_{ws}\mu_{ws}}{\rho_{s1}\mu_{s1}}\right)^{0.1} \left[1 + 0.45(L-1)\frac{h_{D1}}{h_{s1}}\right] \ldots\ldots [A3]$$

Another interpretation of Equation [A2] for high flight speeds

would be to calculate the temperatures as if dissociation did not occur. This would give essentially the same answer as replacing temperature by enthalpy.

Lees (4) has made a careful extrapolation of low temperature compressible boundary layer results and produced the following result for high temperatures

$$q_s = 0.5\sqrt{2}\,\sigma^{1/3}\sqrt{\rho_{s1}\mu_{s1}}\,\frac{h_{s1}}{\sigma}\sqrt{\left(\frac{du_1}{dx}\right)_s} \quad \text{[A4]}$$

Comparison with [A1] shows that the constants are in good agreement for $\sigma = 0.71$. Lees considered only the case of the highly cooled boundary layer; hence the factor $(1 - h_{ws}/h_{s1})$ does not appear in his equation. Apart from this, his result agrees with the interpretation given to Sibulkin's equation. Therefore it also differs from [A1] by the factor given in [A3]. In the region of interesting heat transfer rates for the present calculations this factor has a value of about 1.20. Hence the Lees and Sibulkin formulas are about 20 per cent lower than the results used here.

The calculations on which Equation [A1] is based were made by using the proper variation of fluid properties through the boundary layer under the assumption of thermodynamic equilibrium. Thus the assumptions made by Sibulkin and Lees are not necessary. Addition investigation of the nonequilibrium boundary layer has shown that [A1] can be used with good accuracy even for the nonequilibrium boundary layer, *provided the surface is catalytic*. The possible reduction of heat transfer by use of a noncatalytic surface can also be calculated but this has not been fully investigated yet.

For the purposes of the present paper it is convenient to reduce the heat transfer formula to a function of density and velocity. A large number of calculations of [A1] have been made for different flight velocities and altitudes. The inviscid flow properties needed for these calculations were computed using a Mollier chart constructed from the data of (8); these computations are tedious since solution of the shock wave equations must be done by iteration. Tables of these inviscid flow properties will be published in the near future. To evaluate the velocity gradient at the stagnation point the Newtonian assumption for pressure distribution was used which leads to

$$\left(\frac{du_1}{dx}\right)_s = \frac{1}{R}\sqrt{\frac{2p_{s1}}{\rho_{s1}}} \quad \text{[A5]}$$

Examination of any of the formulas for heat transfer indicates that q_s should vary with density and velocity approximately as $\sqrt{\rho}\,u^3$. A correlation of data computed from [A1] leads to the empirical formula

$$q_s = \frac{20{,}800}{\sqrt{R}}\sqrt{\frac{\rho}{\rho_0}}\left(\frac{u}{u_c}\right)^{3.25}\left(1 - \frac{h_{sw}}{h_{s1}}\right) \quad \text{[A6]}$$

which is accurate to better than 5 per cent. In using [A6] the stagnation enthalpy h_{s1} has been replaced by its hypersonic flow value, $u^2/2$.

APPENDIX B

Constant Heat Transfer Trajectories

Consider a body of mass M travelling with a velocity u in a path approximately tangential to a circle of radius r centered at the earth. Assume that the body can have a lifting force on it of magnitude L. It also experiences a centrifugal force Mu^2/r and an attractive force of $Mg_0r_0^2/r$ due to the earth's gravitational field. Here g_0 is the acceleration of gravity at the surface of the earth and r_0 the radius of the earth. The sum of these three forces must equal the radial acceleration of the body, which may be written Md^2H/dt^2, where H is the altitude of the body above the earth's surface. Thus we have

$$L - \frac{Mg_0r_0^2}{r^2} + \frac{Mu^2}{r} = M\frac{d^2H}{dt^2} \quad \text{[B1]}$$

If the body is travelling in an exact circle with no lift, $L = d^2H/dt^2 = 0$ and its velocity is the circular velocity

$$u_c^2 \equiv g_0r_0^2/r \quad \text{[B2]}$$

which is very nearly constant throughout the whole atmosphere. Now introduce the lift coefficient by

$$C_L = L/\tfrac{1}{2}\rho u^2 S$$

where S is some reference area for lift, and W is the weight which is related to the mass by $M = W/g_0$. Equation [B2] can then be written

$$\frac{C_LS}{W} = \left\{\frac{1}{g_0}\frac{d^2H}{dt^2} + \left[1 - \left(\frac{u}{u_c}\right)^2\right]\right\}/\tfrac{1}{2}\,\rho u^2 \quad \text{[B3]}$$

In this basic force equilibrium equation, r_0/r has been taken to be unity throughout the atmospheric region of interest, and as a consequence u_c will be considered constant.

A similar force equation can be written along the path of the body, where the drag force D causes a deceleration $-du/dt$ by the relation

$$-M\,du/dt = D \equiv \tfrac{1}{2}\rho u^2 C_DA \quad \text{[B4]}$$

Here A is the area on which the drag coefficient C_D is based, and may or may not be the same as the area S. Again using $M = W/g_0$, Equation [B4] becomes

$$\frac{du}{dt} = -\frac{\tfrac{1}{2}g_0\rho u^2}{W/C_DA} \quad \text{[B5]}$$

The analogous parameters C_LS/W and W/C_DA are referred to as the lift and drag parameters, respectively. In ordinary aerodynamic terms the former is the lift coefficient over wing loading.

For any given altitude model the height H is a function only of density. Therefore, Equations [B3, B5] may be looked upon as having two dependent variables ρ and u, both functions of time, which may be determined when C_LS/W and W/C_DA are specified by solving the two differential equations. The heat transfer history of the body could then be found by making use of Equation [1] for the heat transfer rate, which for purposes of analysis may be written

$$q_s = K\sqrt{\rho}u^{3.25}(1 - 2h_{sw}/u^2) \quad \text{[B6]}$$

where K is the constant $20{,}800/\sqrt{\rho_0}u_c^{3.25}\sqrt{R}$.

However, in this paper we propose to investigate constant heat transfer trajectories, and in this case there is a simple relation between ρ and u, given by [B6] as

$$\rho = (q_s/K)^2u^{-6.5}(1 - 2h_{sw}/u^2)^{-2} \quad \text{[B7]}$$

where q_s is a constant. We also assume a simple exponential atmosphere

$$\rho/\rho_0 = e^{-H/c} \quad \text{[B8]}$$

where the scale height c can be chosen most nearly correct in the important heating range.

By combining Equations [B5, B7, and B8]. d^2H/dt^2 can be written as

$$\frac{d^2H}{dt^2} = \left(\frac{g_0}{2}\frac{C_DA}{W}\right)^2 cu^2\left(1 - \frac{2h_{sw}}{u^2}\right)^{-2}\rho^2 \times$$
$$6.5\left\{-5.5 + \left(1.5 - \frac{1}{3.25}\right)\frac{4h_{sw}}{u^2} + 1.5\left(\frac{2}{3.25} - 1\right)\frac{8h_{sw}^2}{u^4}\right\}$$

When this is inserted into [B3] an expression for C_LS/W results

$$\frac{C_LS}{W} = \frac{1 - (u/u_c)^2}{\tfrac{1}{2}\rho u^2} - \frac{g_0c}{2}\left(\frac{C_DA}{W}\right)^2\rho\left(1 - \frac{2h_{sw}}{u^2}\right)^{-2} \times$$
$$\left\{1 - \frac{1.5 - 1/3.25}{5.5}\frac{4h_{sw}}{u^2} - \frac{1.5(2/3.25 - 1)}{5.5}\frac{8h_{sw}^2}{u^4}\right\} \quad \text{[B9]}$$

(Continued on page 147)

Molybdenum for High Strength at High Temperatures

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Molybdenum-base alloys were described at the 1955 ARS Annual Meeting as having the greatest promise for true high temperature operation but the longest development time to actual usage (Reference 1). A. V. Levy of Marquardt Aircraft Co. concluded that the work of applying molybdenum alloys to ramjet structures promised to be both a long road and a rewarding one. The aim of the present paper is to show how far down that road we have come and why the goal is worth the effort.

Introduction

MISSILE and powerplant designers are interested in molybdenum mainly because of its high temperature strength. As a result of a six-year program sponsored by the Office of Naval Research (2),[3] molybdenum-base alloys have been developed with much better high temperature properties than unalloyed molybdenum. These alloys have been found to have higher useful strength at temperatures over 1600 F than any other presently known material. As an indication of the degree of this superiority, Fig. 1 compares the stress rupture properties of molybdenum and three of its alloys with some of the superalloy materials in current or recent use in the jet aircraft field.

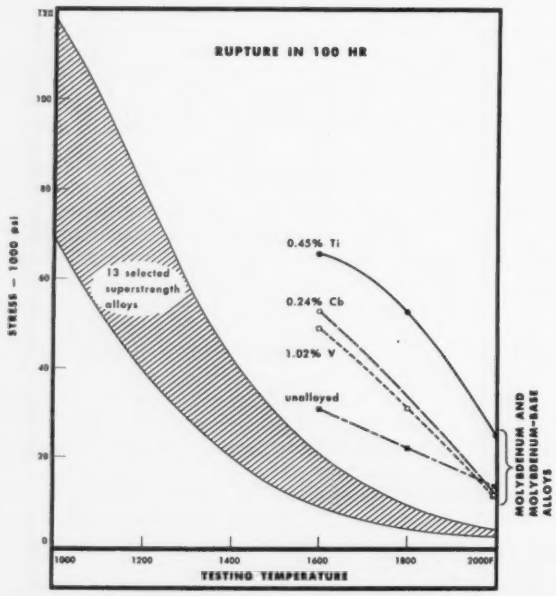


Fig. 1 Stress Rupture strength of molybdenum and three molybdenum-base alloys as compared to the 13 superstrength alloys included in ASTM Special Technical Publication no. 160—molybdenum and molybdenum-base alloys produced by arc-casting process and tested after mechanical working and stress relieving

Four types of arc-cast molybdenum alloys are now commercially available:

0.3% Cb—balance molybdenum
0.5% Ti—balance molybdenum
1.0% V—balance molybdenum
2.0% W—balance molybdenum

Since the 0.5 per cent Ti–Molybdenum Alloy has shown the best all-around combination of properties, major emphasis will be placed on this grade, its properties and processing. Unless specifically mentioned to the contrary, the discussion will be limited to molybdenum made by the arc-cast process. In the jet propulsion field, all indications point to the predominant use of arc-cast molybdenum rather than the powder metallurgy product because of the advantages of the former in respect to available sizes, ease of producing alloys, and fabrication characteristics.

Effect of Composition and Processing

The physical properties of molybdenum appear to be little affected either by the small amounts of alloying elements present in the current molybdenum alloys or by processing. Of particular significance to the high temperature field are the high melting point, high thermal conductivity, high modulus values, and low expansivity (Table 1). On the other hand, mechanical properties are markedly influenced by composition and processing (Figs. 2 and 3). All three alloys have better stress-rupture and creep strength than unalloyed molybdenum in the same condition, and the 0.5 per cent Ti–Molybdenum is the best of the alloys.

Processing is also important. The mechanical properties of unalloyed molybdenum depend to a large degree on the

Table 1 Physical properties of molybdenum metal

Atomic number	42
Atomic weight	95.95
Crystal structure	body centered cubic
Melting point	4730 F
Density—68 F	0.369 lb/cu in.
Electrical conductivity—32 F	34% IACS
Specific heat—70 F	0.061 Btu/lb/°F
Modulus of elasticity (dynamic)	
80 F	45.5×10^6 psi
1500 F	40.
2500 F	35.
Modulus of rigidity	
80 F	17.4×10^6 psi
1600 F	15.
Poisson's ratio	
80 F	0.324
1600 F	0.321
Thermal conductivity	
70 F	68.2 Btu/hr/ft²/ft/°F
1650 F	62.4
Mean coefficient of linear thermal expansion	
68 to 212 F	3.06×10^{-6} per °F
68 to 1832 F	3.41

NOTE: All values determined on unalloyed molybdenum, except thermal conductivity and coefficient of thermal expansion, which were obtained on recrystallized specimens of 0.5% Ti–Molybdenum Alloy.

Presented at the ARS 11th Annual Meeting, New York, N. Y., Nov. 26–29, 1956.

[1] Manager, Arc-Cast Molybdenum Development.
[2] Director of Technical Information.
[3] Numbers in parentheses indicate References at end of paper.

Table 2 Room and elevated temperature tensile properties of 0.5% Ti–Molybdenum Alloy

Bar diam, in.	Condition	Testing temperature, F	Yield strength, psi	Tensile strength, psi	Elongation,[a] %	Reduction of area, %
5/8	As rolled	82	96,700[c]	112,900[b]	29	59.7
		750	78,900[c]	100,400	18	76.1
		1200	80,600[c]	101,300	18	82.6
		1600	81,000[c]	86,900	17	84.0
	Stress relieved, 1 hr—1800 F	80	99,100[c]	132,100[b]	31	70.0
		750	89,000[c]	110,000	18	72.8
		1200	84,000[c]	100,500	17	74.1
		1600	76,500[c]	88,300	15	71.1
	Recrystallized, 1 hr—2450 F	81	60,000	75,500	55	38.0
		750	30,200	45,600	47	86.4
		1200	...	43,700	45	86.2
		1600	15,400	39,900	47	88.4
1	As rolled	77	89,000[c]	115,100	30	46.8
		750	...	90,800	16	75.5
		1200	68,300[c]	84,900	15.5	74.5
		1600	64,800[c]	78,400	15.5	75.0
	Stress relieved, 1 hr—1800 F	83	87,900[c]	113,000	20	25.4
		750	71,300[c]	90,700	17	73.5
		1200	62,600[c]	84,700	16	71.9
		1600	62,800[c]	77,700	16	75.7
	Recrystallized, 1 hr—2600 F	74	53,900	72,500	22	18.7
		750	11,800	42,400	45	83.9
		1200	10,300	39,200	42.5	87.7
		1600	14,500	37,500	48.5	87.6

NOTE: Strain rate 3% per hr within elastic range and 60% per hr within plastic range.
[a] Per cent elongation in 1 in. for 0.250-in.-diam test specimen from 5/8-in.-diam bars; per cent elongation in 2 in. for 0.430-in.-diam test specimens from 1-in.-diam bars.
[b] Different bars.
[c] 0.1%-offset yield strength taken from stress-strain plot; all other yield-strength values from drop in load.

amount of mechanical working done below its recrystallization temperature. The presently available molybdenum alloys are similar in that they are not heat treatable and rely entirely on mechanical working for strengthening. As shown by the data, the high temperature strength of recrystallized material is significantly lower than that of mechanically worked and stress-relieved specimens of the same grade. At 1600 F, recrystallized specimens have about 40 to 50 per cent lower rupture strength than stress-relieved specimens of the same grade. This difference lessens as the testing temperature increases, and disappears if temperature and time are such that the molybdenum recrystallizes during testing.

The effect of alloying additions on recrystallization temperature is consequently of major significance for high temperature service as it sets an upper limit to the operating temperatures where mechanical working can be used for strengthening. For 1-in. rounds, previously given 91 per cent reduction by rolling, the minimum temperature for complete recrystallization in one hour is raised from 2200 F for unalloyed molybdenum to 2600 F for the 0.5 per cent Ti–Molybdenum Alloy.

To summarize, mechanically-worked and stress-relieved 0.5 per cent Ti–Molybdenum Alloy has the best high temperature properties of any of the available molybdenum-base alloys. Additional information on its short-time tensile properties, total deformation, and stress rupture strength is given in Tables 2 and 3, and Fig. 4.

Table 3 Stress to produce rupture in 100 hr of 0.5% Ti–Molybdenum Alloy

Condition	1600 F	1800 F	2000 F
Stress relieved	66000 psi	53000 psi	34000 psi
Recrystallized	34500	28000	21000

NOTE: Values represent averages of closely agreeing figures obtained on two different heats.

Protective Coatings

The rapid oxidation of unprotected molybdenum in air or oxidizing atmospheres at temperatures over about 1000 F is one of the major obstacles to its widespread use at higher temperatures. This problem has been approached from many different angles, and at least 20 laboratories are working on it. Ideas have not been lacking.

If the design permits elimination of oxygen and water vapor from the atmosphere, molybdenum can be used without protection. In some oxygen-deficient combustion gases, for example, uncoated molybdenum appears feasible for temperatures up to 2600 F where an engine life of less than 100 hr is acceptable (3).

Despite considerable research, no one has yet been able to find a molybdenum alloy that combines high oxidation resistance and good high temperature properties, so this solution must be by-passed for the moment.

Consequently, protective coatings seem to be the answer for most applications. Types of coatings that have been tested have included ceramic, cermet, vapor-deposited, hot-dipped, sprayed metal (metallized), electrodeposited, and clad. One company alone recently reported testing over 160 different coatings. Some of these coatings have proved successful on a laboratory scale, and commercially feasible solutions to the protection problem appear to be not too far away, especially where a useful life of 500 to 1000 hr at 1800 F (or shorter times at higher temperatures) is considered acceptable. Major development work today is along the lines of modifying already available coatings, particularly regarding their application on a production basis, rather than looking for wholly new coatings.

The specific requirements placed on coatings will vary with the type of part to be protected, but engineers in general are looking for the following characteristics:

1 Adequate oxidation resistance. While some gas-turbine engineers may be talking about temperatures as low as 1800 F, missile designers are interested only in higher temperatures, usually over 2500 F.

2 Absolute integrity of coating.

3 Resistance to thermal shock, impact, and erosion.

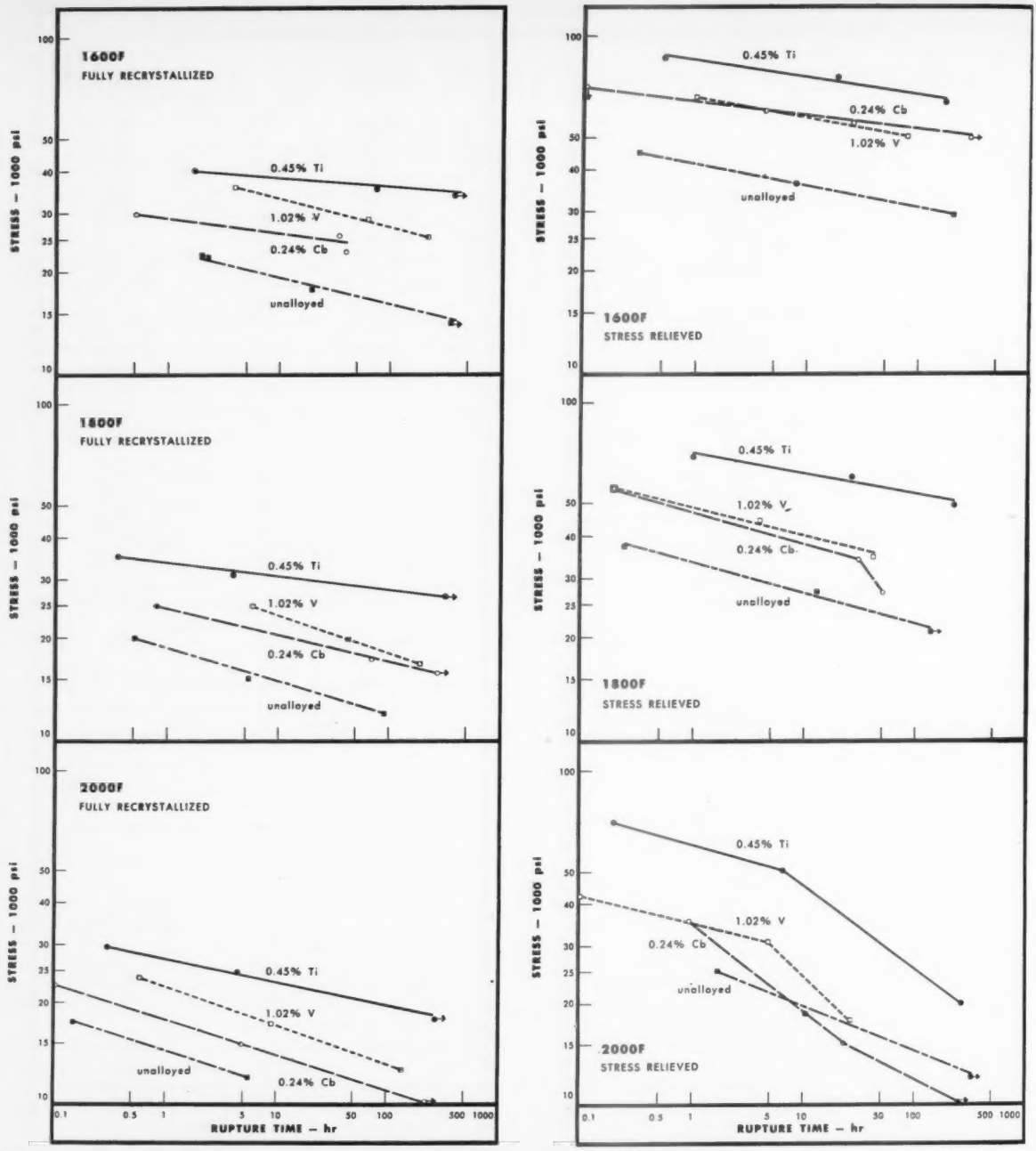


Fig. 2 Stress rupture strength of molybdenum and three molybdenum-base alloys at 1600, 1800, and 2000 F—tests run in vacuum on specimens in stress-relieved and recrystallized conditions

4 Sufficient ductility to withstand some deformation without damage, and, preferably, a certain degree of self-healing for accidental damage.

From the production standpoint, the coating must be capable of:

5 Application to assemblies, complex shapes, edges, hollow parts, and large sheets.

6 Withstanding a reasonable amount of handling and flexure in installation.

7 Protection without adding excessive weight or thickness to parts.

8 Giving a smooth finish, either as coated or as ground.

9 Application at temperatures that will not cause recrystallization of the molybdenum if maximum strength and ductility of coated parts are desired. If brazed parts are to be coated, the maximum processing temperature must be adjusted to the filler metal used.

Ideally, the final tests should be made on actual parts under service conditions to determine if all these requirements are fulfilled. Most laboratories, however, have developed satisfactory tests for at least preliminary screening of coatings. Some of the common tests are described in two Wright Air Development Center reports (4). In addition to simple oxidation tests, they include thermal-shock testing (Fig. 5); ballistic-impact testing (Fig. 6); and erosion testing (Fig. 7).

Among the most promising protective methods for missile

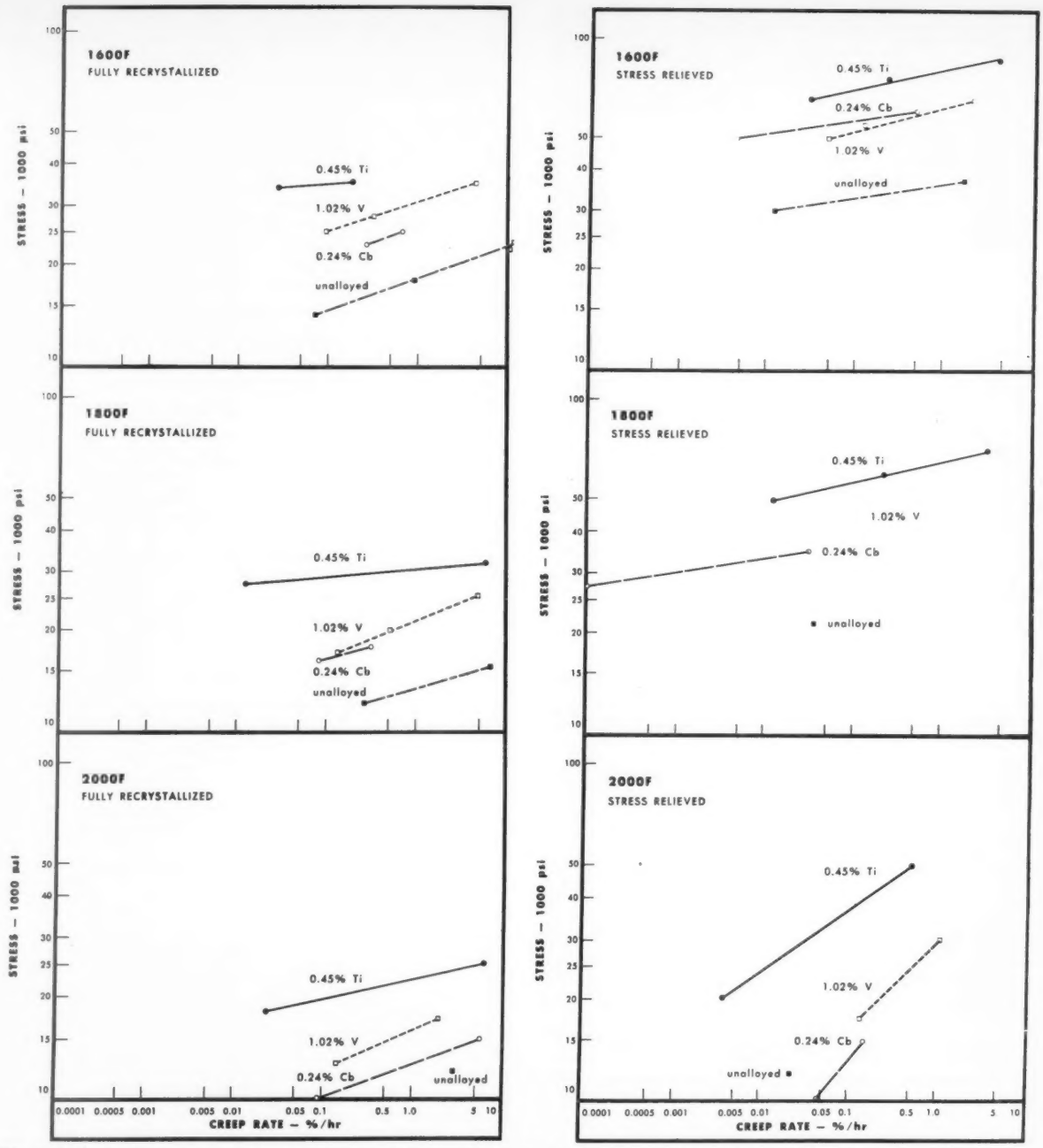
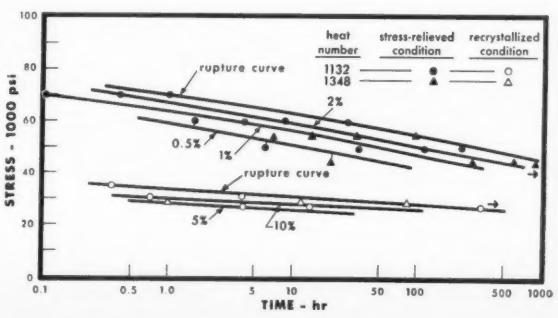


Fig. 3 Second-stage creep rate of molybdenum and three molybdenum-base alloys at 1600, 1800, and 2000 F—tests run in vacuum on specimens in stress-relieved and recrystallized conditions

Fig. 4 Relation between stress and time for indicated amounts of total deformation at 1800 F—tests run in vacuum on specimens from two heats of 0.5% Ti-Molybdenum Alloy in stress-relieved and recrystallized conditions.



components are sprayed-metal and electro-deposited coatings. Since no one coating has proved to be best under all conditions (Table 4), the type of coating must be adapted to the service conditions of the part. In addition to the properties listed in Table 4, the sprayed Al-Cr-Si coating has considerable potential at temperatures above 2500 F. Preliminary tests have indicated a life of at least five hours at temperatures above 3000 F. Moreover, metal-sprayed specimens have shown practically the same 100-hr stress-rupture

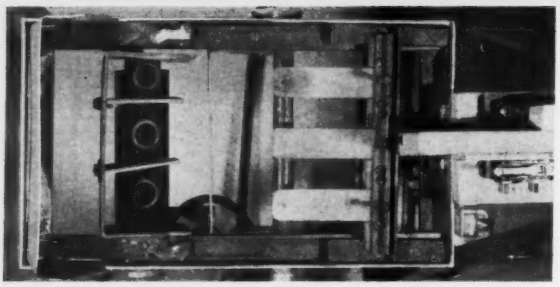


Fig. 5 Thermal-shock testing of coated molybdenum—three samples are heated rapidly to 1800 F in a gas flame, held 15 sec, then cooled to room temperature in an air blast

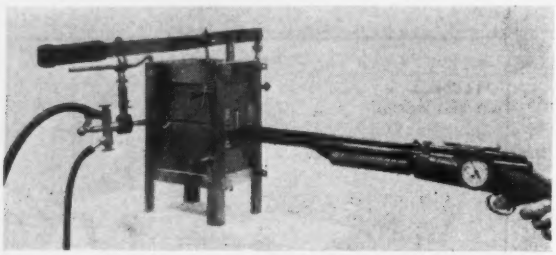


Fig. 6 Ballistic impact testing of coated molybdenum—after heating in a small furnace and hitting with steel shot from an air rifle, the samples are subjected to a static oxidation test in air at 1800 F

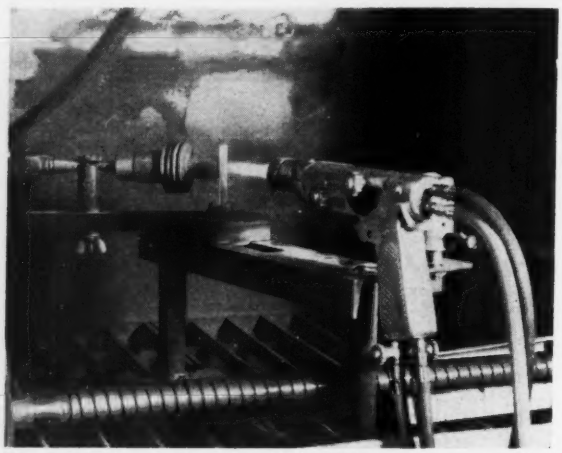


Fig. 7 Erosion testing of coated molybdenum—hot alumina grit is blown on coated specimens to evaluate resistance to erosion

strength at 1800 F when tested in air as uncoated specimens tested in vacuum. They have also withstood 2 per cent elongation during static loading for 100 and 500 hr at 1800 F without coating failures.

The present status of protective coatings can be summarized somewhat as follows:

Up to 2000 F: Metal cladding for relatively simple shapes where maximum surface toughness is essential. Electrodeposited chromium and nickel-chromium alloys, particularly if complex shapes are involved.

Up to 2400 F: Complex metal-sprayed coatings, which are applicable to relatively large and complex shapes and exhibit some self-healing. These coatings are less brittle than ceramics but less ductile than clad or plated coatings.

Over 2400 F: Encouraging results on some sprayed coatings for relatively short exposures. Ceramic and vapor-deposited molybdenum-disilicide coatings hold promise of long-time protection where service does not involve mechanical impact, high stresses, or severe thermal shock.

Fabrication and Joining

Molybdenum can be fabricated by most of the conventional methods with little or no modification. All problems connected with joining, however, have not yet been solved, although welds with adequate ductility for many applications can now be produced.

Forging of bar stock is the most suitable way to produce parts such as solid gas-turbine buckets. Because the commercial molybdenum alloys now available are not heat treatable, the high temperature strength required for engine operation can be obtained only by warm working below the recrystallization temperature. A joint development program of Climax Molybdenum Co., Steel Improvement and Forge Co., and Westinghouse Electric Corp. showed that some modifications had to be made in the practices used for superalloys, but that satisfactory buckets could be produced either by rolling and forging, or by resistance upsetting and forging (Fig. 8). Close control of both the forging stock and forging operations is necessary.

Forming rather than forging is the most practical fabrication method for many types of ramjet parts. With sheet up to about 0.020 in. thick, forming, bending, spinning, and deep drawing can be carried out by the usual procedures at room temperature; but it is better practice to heat both the work and tools. Heavier material must be heated to 200 to 1100 F, depending on size. Recent modifications of the spinning process (such as "Floturning" and "Hydrospinning") offer a possibility of forming thin-wall conicals and cylinders without welding or extensive deep drawing. Room temperature trials with $1/16$-in.-thick unalloyed molybdenum resulted in fracture before appreciable forming had been accomplished; successful results, however, were obtained when

Table 4 Comparative performance of several types of protective coatings on molybdenum

Coating	Oxidation test minimum life, hr 1800 F	Oxidation test minimum life, hr 2000 F	Thermal cycling test minimum life, cycles	Ballistic impact test (330 fps) life at 1800 F after impact, hr	Erosion test life at 1800 F, min
Sprayed					
Single layer Al-Cr-Si	500+	100+	484	0	25 to 30
Single layer Ni-Cr-B	500+	100+	185	500+	55 to 60
Single layer Ni-Si-B	500+	98	108	500+	40 to 50
Ni-Cr-B + Al-Cr-Si	500+	100+	not tested	22	30 to 55
Al-Si + Al-Cr-Si	500+	100+	476	0	not tested
Electroplated[a]					
0.001-in. Cr + 0.007-in. Ni	500+	114+	130[b]	500+	not tested

[a] By National Bureau of Standards.
[b] Separation of nickel from chromium underlayer occurred after approximately 25 cycles.

the molybdenum was heated to approximately 800 to 1100 F prior to forming (Fig. 9).

Molybdenum and its alloys generally have hardnesses under 300 Brinell but are considerably more abrasive to machine than steel at the same hardness. Prior treatment has little effect on machinability. Either high speed steel or sintered-carbide tools can be used for machining; cast cobalt-base alloys have not proved satisfactory. Tool angles and rakes are on the whole similar to those for machining cast iron. A 50–50 mixture of chlorinated oil and trichloroethylene, or highly chlorinated oil is recommended as a cutting fluid. An integral turbine wheel with hollow buckets shows that the machinability of molybdenum is adequate for even complicated parts, provided a small amount of preliminary work is done to establish proper cutting conditions (Fig. 10).

Although small electrical and electronic parts of molybdenum had been successfully welded for many years, the obtaining of ductile welds with good structural properties was a serious problem when research and development on molybdenum for the jet propulsion field were started. In addition to government-sponsored investigations at Battelle Memorial Institute, Massachusetts Institute of Technology, and Westinghouse Electric Corp., valuable programs were inaugurated at various aircraft companies. These studies have proved that arc-cast molybdenum can be welded without porosity and with freedom from cracks. This is generally not true of commercially available molybdenum made by powder metallurgy methods.

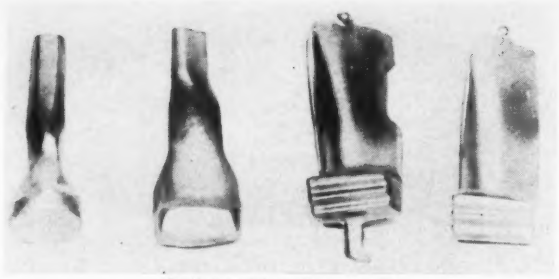
At present, inert-gas shielded-arc welding with tungsten electrodes, with or without filler wire additions, appears to be the most satisfactory method of welding heavy sheets and parts. Some prefer helium to argon because of the greater heat produced at the arc and the resultant narrower heat-affected zone. Welding current and travel speed, which depend largely on the fixtures and chills used, can readily be established by a few trial runs. Straight butt welds are satisfactory for thicknesses up to about $^3/_{32}$ in. Thicker material will generally require multiple passes in a V-butt joint, with preheat and filler wire addition. The filler wire obviously lessens the need for highly accurate fitup.

Two steps to minimize embrittlement are essential and a third desirable. The first of these is extreme cleanliness of faying surfaces and adjacent areas. Electrolytic polishing seems to be the most reliable method of guaranteeing this required cleanliness. The second is the need to control the welding atmosphere carefully with respect to oxygen and nitrogen, both of which have a detrimental effect on ductility. If high quality welds are to be obtained, air must be completely excluded from the molten weld puddle. Finally, a preheat at about 400 to 600 F is decidedly beneficial, particularly when welding complex assemblies.

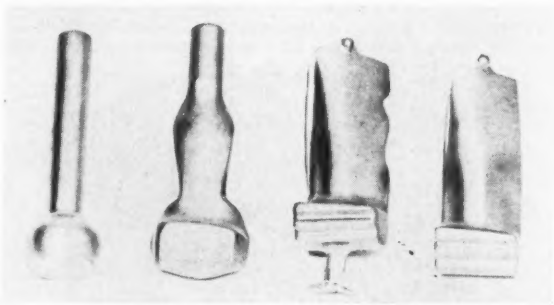
Welds made under optimum conditions still have poor ductility at room temperature, but bend-test data show significant ductility in the as-welded condition when tested at 300 F or higher. Heating to approximately 500 to 600 F is therefore mandatory when weldments are to be formed or roll-leveled. Figs. 11, 12, and 13 are examples of molybdenum weldments made under relatively commercial conditions.

Ductility of brazed joints may be superior to welded joints provided the time at temperatures above about 1700 F is kept to a minimum. Brazing, however, is not universally suitable. Moreover, filler alloys adaptable to relatively low temperature brazing (and which avoid embrittlement of the parent metal) are unsatisfactory for high temperature applications. Although many brazing alloys have been tried for high temperature structural applications, and some have given encouraging results for certain parts, none has as yet proved satisfactory for all applications (Fig. 14).

Riveting and other mechanical means of joining offer possibilities for applications that must not be gas or liquid tight. Little has yet been done to determine the feasibility of com-



Rolled and forged approach



Westinghouse Electric Corp.

Resistance upset and forged approach

Fig. 8 Successive stages in forging gas turbine buckets of 0.5% Ti-Molybdenum Alloy—satisfactory buckets could be produced either by rolling and forging, or by resistance upsetting and forging; but the latter approach was more efficient and gave a more uniform product (approx. $^1/_3$ natural size)

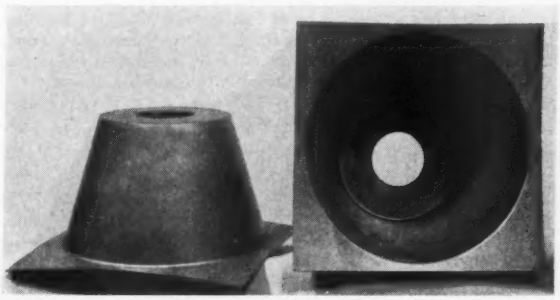
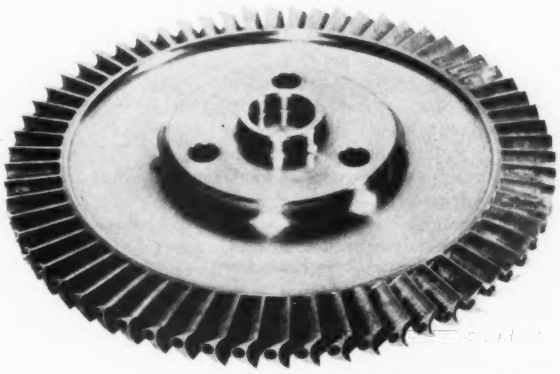


Fig. 9 Cones "Floturned" from 0.058-in.-thick unalloyed molybdenum sheet at approx. 800 to 1100 F (approx. $^1/_4$ natural size)



Experiment Incorporated

Fig. 10 Integral molybdenum turbine wheel with 63 drilled buckets—wheel finish machined from rough-machined forging, 9 in. diam × 2 in. thick × 47 lb (approx. $^1/_3$ natural size)

Wright Aeronautical Div., Curtiss-Wright Corp.

Fig. 11 Molybdenum flame gutter, 20-in. diam—fabrication consisted of joining inner and outer annular ring segments with a weld at the apex junction, and subsequently butt welding the segments to make a continuous ring; helium-shielded arc welding used; a 400 F preheat was maintained during welding

Wright Aeronautical Div., Curtiss-Wright Corp.

Fig. 12 Six-in.-diam molybdenum nozzle, arc welded with helium shielding—the two cone sections were welded together automatically with addition of commercially-pure molybdenum filler wire; the upper cone was expanded at 600 F after welding so the ends were flared sufficiently to meet the flange

binations of mechanical joints (as lock seams) with subsequent brazing or welding.

In summary, there are no insuperable problems in fabricating and joining molybdenum, although more precautions have to be observed than with superalloys. While welds with high ductility at room temperature have not yet been achieved, tremendous progress in this direction has been recorded in recent years and welds with satisfactory properties for many high temperature applications can now be made commercially.

Applications in the Jet Propulsion Field

In discussing the high temperature material requirements of the Air Force, Colonel R. A. Jones (5) pointed out that in the past the materials problems facing aeronautical designers were dwarfed by stability, control, engine, and propeller design problems. Today, the situation is reversed, and more and more often the statement is heard that "the limiting factor is suitable heat-resistant materials." This is ample explanation for the research and development effort expended on molybdenum.

The jet propulsion field—including guided missiles and aircraft powered by rocket, ramjet, and turbojet engines—covers a tremendous variety of requirements and service conditions in respect to temperature, atmosphere, amount, and type of stress, vibration, thermal shock, and prospective life. Molybdenum's properties make it a logical choice in a number of cases, because it has:

1 High creep and rupture stress, particularly at temperatures over about 1600 F. This applies not only under tensile stresses (Figs. 1, 2, 3, 4, and Table 3) but also under compression stresses (Table 5). The tensile stresses are

Wright Aeronautical Div., Curtiss-Wright Corp.

Fig. 13 Welded molybdenum tube, 6 in. diam × 4 ft long—continuous automatic arc welding carried out with helium shielding and without filler-wire addition; preheat of approx. 400 F maintained during welding

significant for parts such as gas-turbine buckets; the compressive stresses, for frame and skin applications.

2 High tensile strength at high temperatures. The

Table 5 Compression creep properties at 1600 F of unalloyed molybdenum and four high temperature alloys (6)

	Creep deformation, %	Stress, psi, for creep deformation in: 10 hr	50 hr	100 hr	200 hr
Wrought S-816	0.5	4,700	2,600	...	...
	1.0	5,800	3,500	2,800	...
	2.0	7,300	4,600	3,700	3,000
	5.0	10,100	6,100	4,800	3,900
Wrought Nimonic 90	0.5	5,700	3,100	...	...
	1.0	6,400	4,100	2,500	...
	2.0	...	5,000	3,500	1,800
	5.0	...	6,200	5,100	3,000
Cast Haynes Stellite 21	0.5	...	...	...	...
	1.0	14,800	...	...	...
	2.0	17,000	14,400	13,300	...
	5.0	21,500	17,800	16,500	...
Metamic LT-1	0.5	19,200	17,800	16,900	16,200
	1.0	24,000	19,100	18,000	17,300
	2.0	25,500	21,100	19,500	18,000
	5.0	26,700	22,100	20,600	18,900
Swaged Molybdenum[a]	0.5	31,400	26,500	24,300	22,800
	1.0	32,200	28,500	26,500	24,500
	2.0	33,200	30,500	28,300	25,800
	5.0	...	31,600	30,400	27,700

[a] Tested in air with metallized chromium-silicon coating for protection against oxidation.

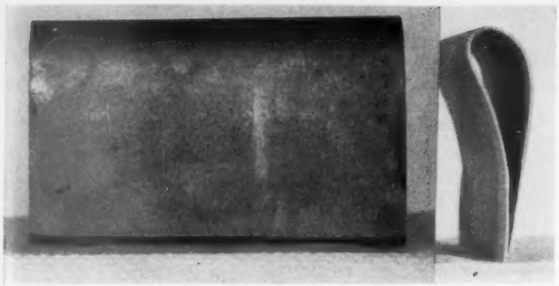
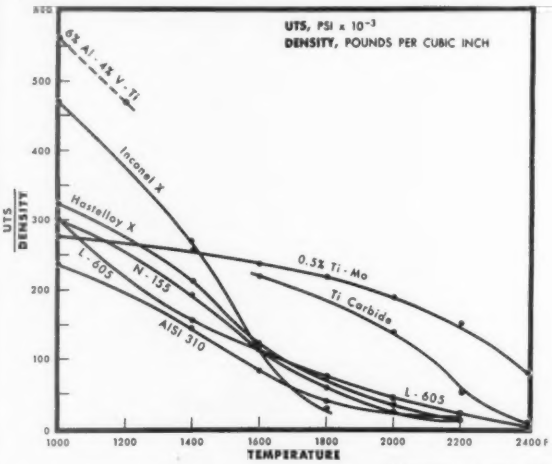
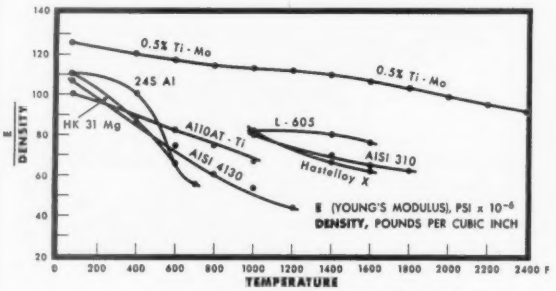


Fig. 14 Gas turbine guide vane made from 0.040-in.-thick molybdenum—Guide vane warm stretch-formed and brazed with AMS 4775 alloy in a hydrogen atmosphere (approx. $^2/_3$ natural size)



Marquardt Aircraft Co.

Fig. 15 Ultimate tensile strength-density ratio vs. temperature for combustor materials



Marquardt Aircraft Co.

Fig. 16 Young's modulus of elasticity-density ratio vs. temperature for diffuser and combustor materials

tensile strength–density ratio of the 0.5 per cent Ti–Molybdenum Alloy shows its superiority to other combustor materials at temperatures above 1600 F (Fig. 15). It therefore can provide structures with optimum strength and minimum weight under transient and steady heating conditions at supersonic speeds where effects of aerodynamic heating on strength must be taken into account.

3 High modulus of elasticity, which is particularly significant for compression and buckling applications. The 0.5 per cent Ti–Molybdenum Alloy is outstanding compared to other diffuser and combustor materials even when its density is considered (Fig. 16).

4 A combination of high thermal conductivity, low specific heat, and low expansivity (Table 1), which minimizes nonuniform temperature distribution and makes molybdenum insensitive to thermal shock.

5 High resistance to erosion by hot gases. A comprehensive series of tests by a manufacturer of aircraft parts shows that molybdenum is considerably better than other materials that might be considered for nozzles (Figs. 17, 18).

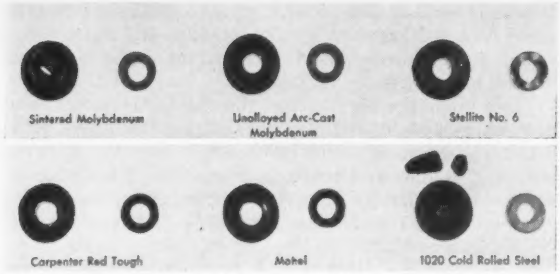


Fig. 17 Comparative resistance of various materials to erosion by hot gases—inserts about $^3/_8$ in. OD × 0.050 in. ID × $^1/_4$ in. long exposed to high speed, high pressure gases at estimated temperature of 2500 to 3000 F

Material	No. Cycles	Remarks
Carbon steel (cold rolled 1020)	20	failed because bits of metal from insert plugged up hole
Sintered molybdenum	29	only a slight amount of erosion but insert seemed to have collapsed; no explanation for better results with arc-cast molybdenum
Alloy tool steel (Carpenter's 883 Red Tough)	52	extensive erosion
Monel Metal	67	considerable erosion
Cobalt-base weld deposit (Stellite No. 6)	95	appreciable erosion
Arc-cast unalloyed molybdenum	100+ (no failure)	no erosion

Fig. 18 Arc-cast molybdenum insert after 100 cycles of exposure to high speed, high pressure gases at estimated temperature of 2500 to 3000 F—insert, about $^3/_8$ in. OD × 0.050 in. ID × $^1/_4$ in. long, retained in housing by spinning; edge of port uneroded, but insert cracked and insert retention ring eroded; overlapping metal that held insert in place was worn away so gas may have penetrated behind insert with considerable force; design changes would probably have overcome this, but project dropped

6 High melting point (Table 1). The melting point is a factor in certain applications where the surface must remain smooth for short periods up to the melting temperature

to permit laminar flow of air at high velocities. Molybdenum's high melting point permits retention and maintenance of uniform and predictable dimensions during the short time the part is operative.

These properties are therefore the clue to the present and potential uses of molybdenum in the jet propulsion field. The first applications, as might be expected, were for parts not involving welding and coating. These were mainly for resistance to erosion by hot gases, such as protecting leading edges of internal guide vane assemblies, and nozzle inserts (Figs. 19, 20, and 22).

In addition, molybdenum and its alloys have been under serious consideration for a number of other parts and in some cases several years of development work have already been done to evolve satisfactory designs. Generally, adoption of molybdenum was slowed down in the initial stages by the need for simultaneous development of better protective coatings and improved welding methods. Under present conditions, it looks as if molybdenum and its alloys stand a good chance of being used successfully for the following applications, all of which involve temperatures over 1600 F:

Gas-turbine buckets for jet planes (Fig. 8) and other applications (Fig. 10).

Gas-turbine guide vanes for jet planes (Fig. 14).

Exhaust nozzles and nozzle liners for ramjets (Figs. 12, 20, and 22).

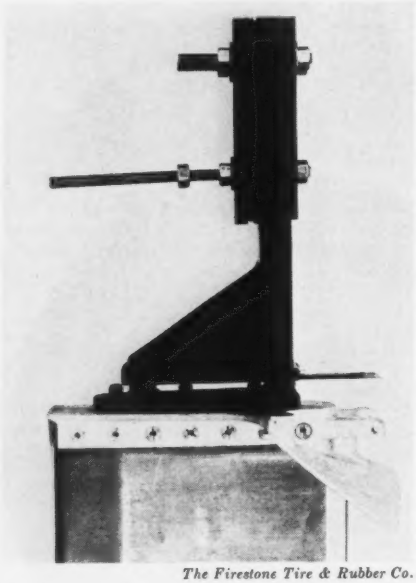
Flameholders and flame gutters for ramjets (Figs. 11, 21, and 23).

Combustion chambers for ramjets.

Leading edges of missiles.

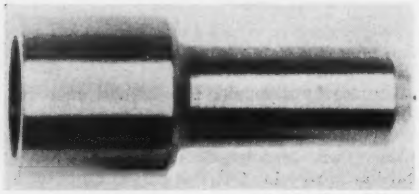
At some future date, even broader applications may evolve if it proves feasible to develop a combination of extremely thin molybdenum sheet and a lightweight honeycomb section.

In conclusion, there seems no doubt that molybdenum-base alloys will become important structural materials in the jet propulsion field and will be essential for many parts operating at temperatures over 1600 F. Research and development have been long and costly, but have resulted in a material that permits true high temperature operation.



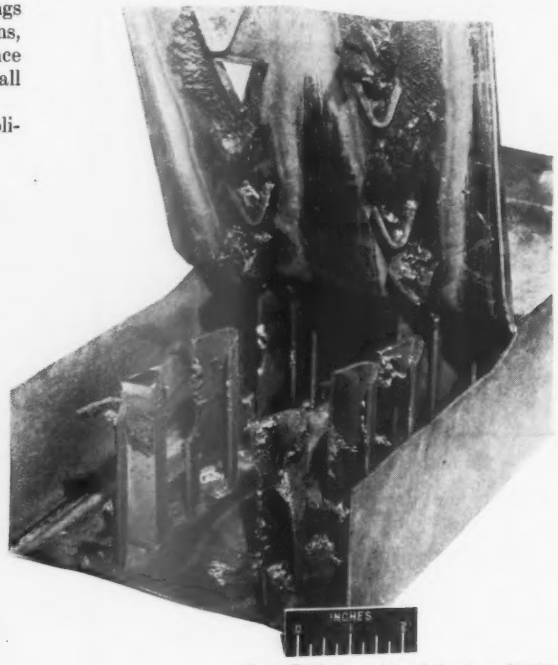
The Firestone Tire & Rubber Co.

Fig. 19 Molybdenum inserts used to protect leading edges of internal carbon guide vane assembly from gas erosion—sintered molybdenum adopted because of its greater availability when design standardized



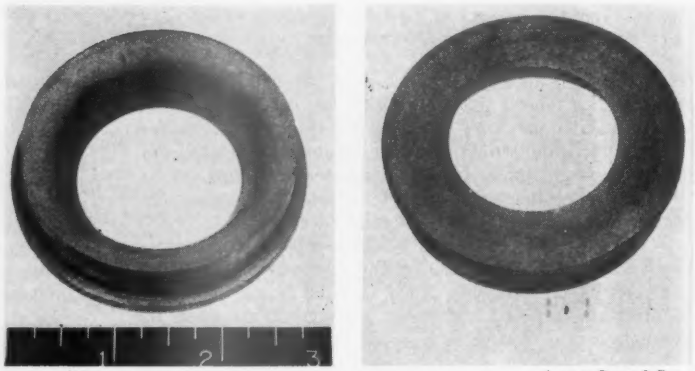
Aerojet-General Corp.

Fig. 20 Molybdenum turbine-inlet nozzle insert being used successfully in a small package power-unit rocket engine—this part is subjected to carburizing gases at 2200 F with a gas velocity at the throat of 5100 fps; (approx. twice natural size)



Lewis Flight Propulsion Laboratory, NACA

Fig. 21 Comparative performance of Inconel and siliconized molybdenum in ramjet flameholder—flameholder made of Inconel with one of downstream gutters replaced by siliconized powder metallurgy molybdenum; after 5 min of operation, molybdenum prism intact amid remains of several melted Inconel gutters (Ref. 7)



Aerojet-General Corp.

Fig. 22 Molybdenum nozzle insert used with satisfaction in a solid engine sustainer capable of 2200-lb thrust for 33-sec duration—flame temperature about 3000 F; gas flow approached 11 lb/sec

Lewis Flight Propulsion Laboratory, NACA

Fig. 23 Performance of siliconized molybdenum in ramjet flameholder—flameholder had same dimensions as in Fig. 22 except the last five gutters in each row were replaced by siliconized powder metallurgy molybdenum prisms; after 47 min of operation, molybdenum was only slightly oxidized in local spots where coating apparently failed (Ref. 7)

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Re-entry Heat Transfer to Satellite Vehicles

(*Continued from page 137*)

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Recovery of Rocket Powered Vehicles and/or Their Components

(*Continued from page 131*)

7 Summarization

In the end-item to be developed for any drag-device application, the type of structure employed and the materials used would be predicated upon both the loads and temperatures to be encountered in flight. As shown in one of the previous sections, the drag loads at low altitude and high speed can be very high and may require the use of built up structure and high strength materials to withstand the loads. On the other hand, operation at high altitude generates very small drag loads. Low altitude, high speed operation can also result in very high temperatures. The high loading combined with high temperature will, for many configurations, preclude the use of such materials as aluminum and will require the use of special alloy steel or certain critical materials such as titanium. For a given drag area of the braking device (say 16 sq ft) it can be shown that a vehicle with a speed equivalent to $N_M \backsimeq 5.0$, and weighing less than 10,000 lb, would decelerate rapidly at altitudes less than 100,000 ft in unpowered flight. This means that the probability of $N_M \geq 5.0$ flights below 100,000 ft is small, and that a scaling of Mach number with altitude would be in order. This would allow lower loads and temperatures to be developed at the lower altitudes with resulting lower structural requirements. In designing the drag device, strength requirements and temperature will have to be balanced against weight and packaging requirements. This type of comparison will serve to further categorize the braking device configurations as to their possible usefulness. If a Mach number scaling with altitude is used, as discussed previously, the number of useable configurations should be greater and will allow a design choice on the basis of cost and dependability as well as brute strength.

At the present time the utilization of parachute recovery techniques is limited to conditions of approximately $N_M = 2.0$ or q (dynamic pressure $= \frac{1}{2}\rho V^2$) approximately equal to 1650, whichever is the lower value, and for loads less than approximately 5000 lb. The extended possibilities for parachutes will most likely lie in directions of more adequate materials and different canopy shapes to relieve the effects of temperature.

Several of the various braking devices, for which some data and/or operating principles are known, have been described in one of the foregoing sections. A comparison of their relative merits has been prepared and is presented in Table 2. As stated, the listing is not intended as complete and is presented for the purposes of indicating significant possibilities.

Great advances may be gained from the investigation of promising fields, such as variable nose shapes, utilization of spoilers and dive brakes, and newer construction and insulation materials and/or methods. Present scopes of work outline the requirements for intensive work in these and related fields at all levels, from basic theory to practical testing.

It is certain that the recovery problem must be adequately solved before man may take his first step into outer space.

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Some Experiments With Two-Dimensional Cavitating Venturis

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General Electric Company, Ballston Spa, N. Y.

Tests were made with two-dimensional cavitating venturis to obtain data of: (a) pressure distribution along a venturi as a function of geometry, (b) the cavitating profile by means of high speed photography, (c) flow control by fluid injection.

Introduction

CAVITATING venturis have been used as flow control devices.[3] The purpose of the experimental work reported in this paper was to study the effect of geometry on venturi operation and also to explore the capabilities and potentialities of venturis as flow controllers. Water was used in all tests.

The investigations can be conveniently subdivided into three phases: Phase 1 consists of obtaining the pressure distribution along a venturi as a function of geometry. Phase 2 consists of high speed photographic studies of the cavitation profile. Phase 3 consists of tests in which fluid is injected into various points of the venturi. Two different methods were tried: In the so-called "closed loop system" some fluid was withdrawn from a point in the venturi and injected into another. In the other, which shall be called "external injection," fluid was injected from an external pressurized source into some point of the venturi.

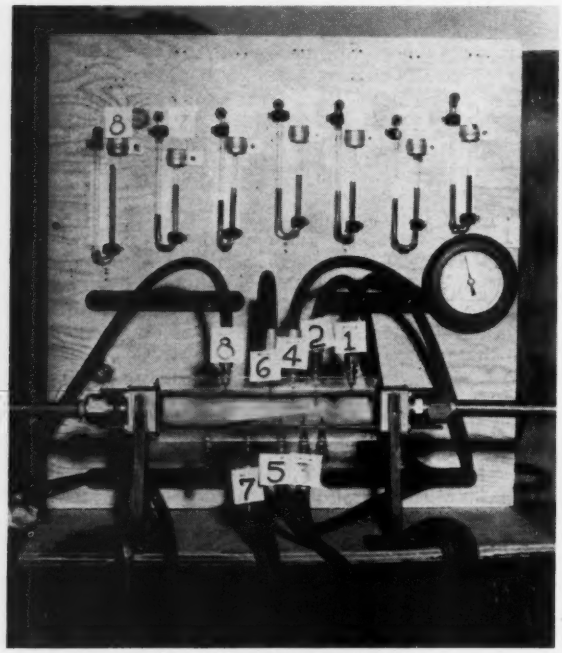

Fig. 1 View of test equipment

Presented at the ARS Fall Meeting, Buffalo, N. Y., Sept. 24–26, 1956.

[1] Supervisor, Combustion Development Unit, Rocket Engine Section, Malta Test Station. Mem. ARS.

[2] Presently with Griscom-Russell Co., Massillon, Ohio.

[3] See Randall, L. N., "Rocket Applications of the Cavitating Venturi," *Journal of the American Rocket Society*, vol. 22, 1952, p. 28.

[4] Manufactured by Rohm & Haas Co.

Apparatus

In all, ten two-dimensional venturis were fabricated from Plexiglas.[4] Five of these venturis had a constant convergence half-angle of 45 deg and divergence half-angles of 2 to 6 deg in 1 deg intervals. The remining five venturis had a constant divergence half-angle of 4 deg and convergence half-angles of 15 to 90 deg in 15 deg intervals. The area of the throat was held constant for all of the venturis. Provision for obtaining pressure measurements (eight to ten pressure taps dependent upon space limitations) were provided in each venturi.

The venturis were placed in a water line whose pressure was supplied by pumps. A hand-operated valve was located downstream of the venturi through which different back pressure could be exerted at the venturi discharge.

Fig. 1 is a view of the test rig. It was necessary to use closed end mercury filled manometers to obtain satisfactory pressure measurements in the cavitation region.

In Phase 2 of this program, the only special equipment was a Wollensak 16-mm Fastax camera that was operated at a film speed of 1000 frames per sec.

In Phase 3 of this program the only special equipment required was a 9-qt tank which contained the water supply for injection plus a source of high pressure gas.

Discussion of Tests and Results

Phase 1

As was previously stated, Phase 1 of the program consisted of obtaining information concerning the pressure distribution along a venturi as a function of geometry. This was accomplished by testing each venturi at two constant upstream pressures (72 psia and 102 psia) and varying the back pressure from the minimum obtainable, due to downstream piping, in 10 psi intervals up to incipient cavitation.

Incipient cavitation is that operating condition in which a further increase in back pressure will change the weight flow rate passing through the venturi. From this series of tests it was possible to obtain four pieces of information. However, it should be noted here that all of this information must be considered qualitative unless specifically applied to venturis identical with those tested.

Fig. 2 is a plot of the back pressure at the venturi exit vs. the length of cavitation as measured downstream of the throat. It was not possible to determine accurately the end of cavitation for the venturi that had a 5 and 6 deg divergence half-angle due to random oscillation of the interface between the end of cavitation and the liquid zone downstream.

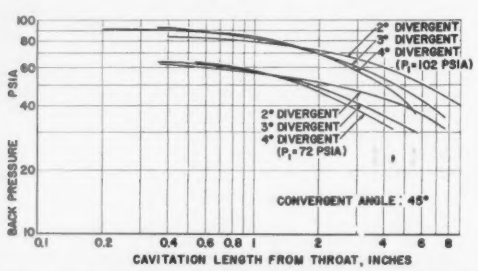

Fig. 2 Length of cavitation region as a function of back pressure at venturi exit

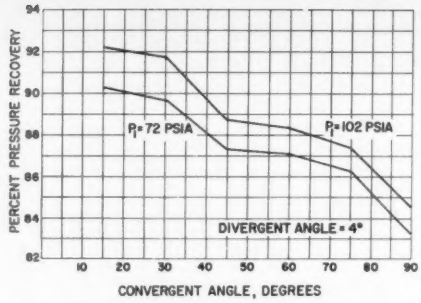

Fig. 3 Pressure recovery as a function of convergence angle

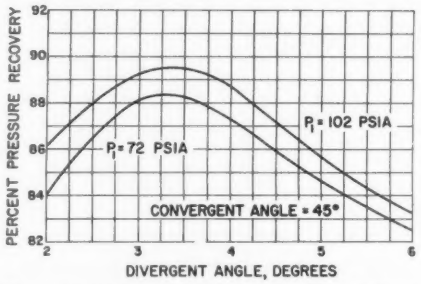

Fig. 4 Pressure recovery as a function of divergence angle

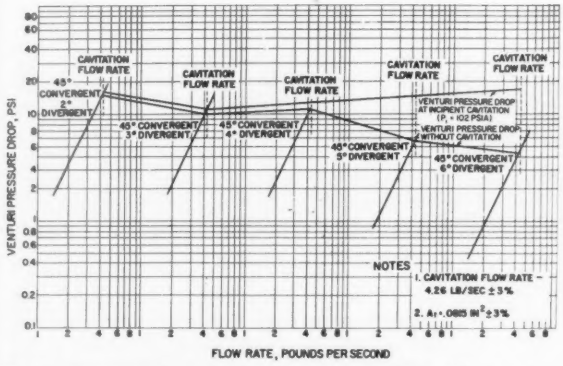
VENTURI PRESSURE DROP, PSI
CAVITATION FLOW RATE
45° CONVERGENT 2° DIVERGENT
45° CONVERGENT 3° DIVERGENT
45° CONVERGENT 4° DIVERGENT
45° CONVERGENT 5° DIVERGENT
45° CONVERGENT 6° DIVERGENT
VENTURI PRESSURE DROP AT INCIPIENT CAVITATION (P_1 = 102 PSIA)
VENTURI PRESSURE DROP WITHOUT CAVITATION
NOTES
1. CAVITATION FLOW RATE = 4.26 LB/SEC ± 3%
FLOW RATE, POUNDS PER SECOND

Fig. 5 Pressure drop along the venturi under incipient cavitation and "extrapolated" no-cavitation conditions

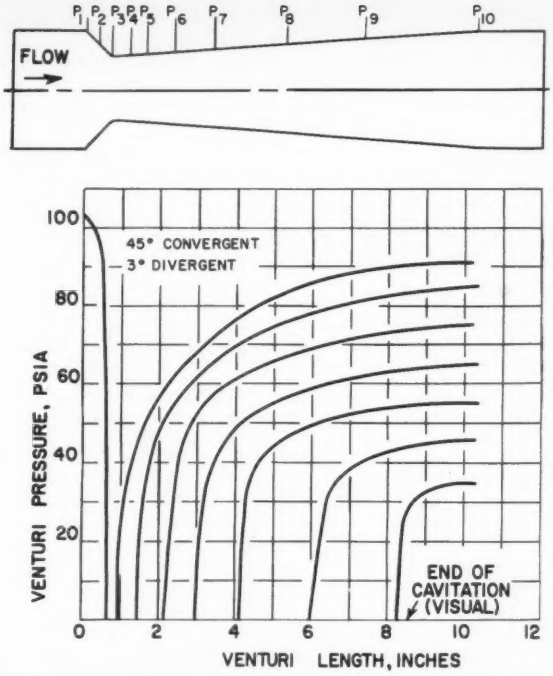

Fig. 6 Pressure distribution along a cavitating venturi at various back pressures

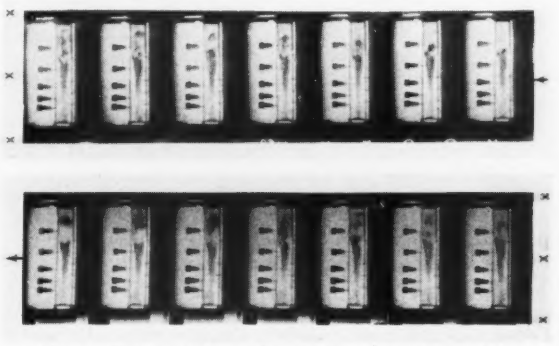

Fig. 7 Fastax pictures of cavitating venturi operation

Fig. 3 is a plot of the pressure recovery vs. convergence half-angle holding the divergence angle constant. The pressure recovery is defined in equation form as

$$\text{pressure recovery, } \% = \frac{P_d}{P_u} \times 100$$

where P_u is the upstream pressure and P_d is the downstream pressure, at incipient cavitation conditions. The precision of the measurement is approximately 3 per cent.

Fig. 4 is a plot of the pressure recovery vs. divergence half-angle for a constant convergence angle.

Fig. 5 is a plot of the pressure drop along the entire venturi as a function of the flow rate under noncavitating conditions through constant convergence angle venturis at various divergence angles. These five individual lots were then extrapolated to the same flow rate that is established under cavitating operation. Superimposed upon this plot are the actual experimental pressure drops obtained across these same venturis at incipient cavitation. This provides a comparison of the pressure drop with and without cavitation. It may be noticed that, for the smaller divergence angles, the additional pressure drop due to cavitation is small; at divergence angles greater than 4 deg, it becomes rather appreciable. The magnitude of the pressure drop with incipient cavitation is largest at 2 deg, decreases to its minimum at 3 deg, then increases. At the same time the pressure drop is decreasing as the divergence angle increases, since for the smaller angles the venturi surface length is longer. These three factors combined could possibly explain the peaking of the pressure recovery at $3^1/_2$ deg in Fig. 4.

Fig. 6 is a plot of the pressure distribution along the venturi length. The cavitation regions were determined visually from photographs.

Phase 2

The operation of a 45-deg convergent, 6-deg divergent venturi was photographed with a 16-mm Fastax camera at a frame speed of 1000 frames per sec. The pictures indicate that the cavitation zone does not possess steady boundaries. The transition between the cavitation region and downstream liquid zone was not stable. The front oscillated periodically shedding vapor pockets. These moved downstream with a very discernible rotation till they were finally absorbed. Fig. 7 shows Fastax frames illustrating these phenomena.

Table 1 Results of tests with venturi using closed loop liquid injection

Injection procedure	Supply pressure, psia	Injected flow rate, lb/sec	Flow rate, no injection, lb/sec	Flow rate, with injection, lb/sec	Flow rate decrease lb/sec	Flow rate decrease %	Flow rate increase lb/sec	Flow rate increase %
From P_2 to P_2	50	..	2.76	2.50	0.26	9.4	..	..
From P_2 to P_3	76	..	3.30	3.14	0.16	4.8	..	..
From P_2 to P_3	107	..	3.80	3.68	0.12	3.2	..	..
From P_2 to P_4	68.5	..	3.15	3.35	..	..	0.20	6.0
From P_2 to P_5	68.5	..	3.15	3.29	..	..	0.14	4.3
From P_{10} to P_3 No cavitation	74	..	2.95	2.70	0.25	8.5	..	..

Table 2 Result of tests with venturi using external flow injection

Injection procedure	Supply pressure, psia	Injection flow rate, lb/sec	Flow rate, no injection, lb/sec	Flow rate, with injection, lb/sec	Flow rate decrease lb/sec	Flow rate decrease %	Flow rate increase lb/sec	Flow rate increase %
Into P_2	70	0.22	3.19	2.49	0.70	21.9	..	..
Into P_3	72	0.24	3.21	2.45	0.76	23.7	..	..
Into P_3	90	0.20	3.52	3.04	0.48	13.6	..	..
Into P_2	93	0.23	3.59	2.98	0.61	17.0	..	..
Into P_4	75	0.17	3.25	3.41	..	..	0.16	4.7
Into P_5	73	0.21	3.22	3.47	..	..	0.25	7.2
Into P_3 No cavitation	85	..	..	..	..	..	..	..
Into P_3 and P_{3a}	72	0.30	3.21	2.48	0.73	22.7	..	..
Into P_3 and P_{3a}	93	0.29	3.59	2.96	0.63	17.5	..	..

Phase 3

Some exploratory tests were attempted to determine whether a venturi could be used as a control device by employing a small flow to modulate a large flow. A 60-deg convergent, 4-deg divergent venturi was used in this investigation. This phase was divided into two parts. The first part consisted of a closed loop system, which was explained previously. Fig. 8 is a schematic of the venturi's tap locations.

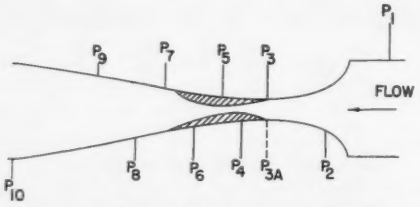

Fig. 8 Schematic of venturi's tap location

A tabulation of the results for a closed loop system is shown in Table 1. The reduction or increase in flows are computed on the basis of constant upstream pressure, i.e., the same upstream pressure during normal and injection conditions.

A tabulation of the results for the second part of this phase using the external injection system is shown in Table 2. The venturi used was modified to include tap P_{3a} located at the throat.

When fluid is injected downstream of the throat, i.e., into P_4 and P_5, it should be noted that in the closed loop system a pressure decrease was experienced at P_1, while in the external system an increase in P_1 was obtained.

Conclusion

In the design of venturis, the geometry is of prime importance for good pressure recovery. It apparently does not affect the pressure distribution along the cavitation length. In addition, the stability of the interface between the cavitation region and downstream liquid zone apparently depends on the divergence angle geometry.

It would appear that a small flow injected into a venturi will modulate a large flow. Two methods were used to accomplish this flow modulation. The increase in throat pressure during injection at the throat is significant, since it is possibly the mechanism by which this modulation is accomplished.

Acknowledgment

This work was performed as part of a contract with the Ordnance Department of the Department of the Army. We wish to thank them for permission to publish this paper.

NEXT MONTH . . .

JET PROPULSION will present a special review of high altitude sounding rockets under the editorship of Homer E. Newell, Jr., of the Naval Research Laboratory. Leading authors will cover the latest research rockets in detail as well as some probable rocket designs of the future.

A Generalized Closed Form for Burnt Velocity

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The equation of motion of a rocket neglecting gravitational field forces, is integrated in closed form to yield a useful, easily applied design equation. In performing the integration, no assumptions are made concerning the dependence of the drag and thrust terms. Calculations of the burnt velocity, therefore, are easily performed for any variation of the drag coefficient with Mach number. Calculations and design graphs are given for those drag functions of most practical interest. Included is the case wherein the drag coefficient is constant at subsonic velocities, has a finite jump at Mach 1, and decays with increasing Mach number. Additionally, for a specified maximum thrust, it is shown that definite limits exist on the attainable velocity. This limiting velocity is independent of the propellant mass to inert mass ratio.

Nomenclature

a, b = empirical constants in the drag coefficient–Mach number relationship (see Equation [24] or K_d, below)
c' = velocity of sound in the undisturbed atmosphere
d = diameter of the projectile (see Ref. 5, p. 9, Note 1)
D = drag force, $K_d \rho d^2 v^2$
$\bar{F}$ = summation of all external forces acting on the rocket (F = magnitude of these forces)
H, G = dimensionless parameters giving the effect of launching velocity on the mass ratio (see Equations [22, 29])
K_d = drag coefficient, defined by Thomas (Ref. 5) as

$$K_d = b^2 + 2ab/M + (a^2 - 1)/M^2$$

m = instantaneous mass of the rocket
m_p = initial mass of the propellant
$\dot{m}_g$ = mass rate of discharge of the exhaust gases issuing from the rocket nozzle
M = flight Mach number of the rocket
M' = Mach number of the rocket exhaust gases, i.e., the relative velocity of the exhaust gases divided by the sonic velocity in the undisturbed atmosphere
T = rocket thrust defined by Equation [4]
t = time, seconds
v = velocity (more correctly, speed) of the rocket
v' = velocity (speed) of the rocket exhaust relative to the rocket; equal to specific impulse multiplied by gravitational acceleration
ν = v/v'
δ = a positive dimensionless parameter defined by Equation [14].

Subscripts

b = instant that all the propellant has burned out, i.e., "burnt" or "burnout"
o = instant of launching or initial values

Introduction

IN DESIGNING many rockets it is common practice to compute the burnt velocity v_b from the familiar equation

$$v_b = v_o + v' \ln \frac{m_o}{m_b} \quad \ldots\ldots [1]$$

The shortcomings of this equation are well known and stem principally from neglecting the effects of aerodynamic drag on the rocket motion.

In this paper, this limitation is removed, the equation of motion is integrated, and a more realistic design formula is thus obtained. The revised formula may be used directly in lieu of Equation [1] or simply in conjunction with [1] to evaluate the effects of drag on the over-all design.

Analysis

The equation of motion of a rocket is given in (1)[3] as

$$\bar{F} - \dot{m}_g \bar{v}' = m \frac{d\bar{v}}{dt} \quad \ldots\ldots [2]$$

wherein

$$m = m_o - \int_0^t \dot{m}_g dt_1 \quad \ldots\ldots [3]$$

The following assumptions are now introduced:

1 The $\bar{v}$, $\bar{F}$, and $\bar{v}'$ vectors are assumed to be co-linear for all time, i.e., the effects of yaw and trajectory curvature are disregarded. This, of course, implies that gravitational field forces are neglected.

2 The only external force acting on the rocket is aerodynamic drag; thus $\bar{F}$ is equal to the drag.

3 The pressure differential at the exit plane of the nozzle is disregarded (see (1), p. 9, Equation 1.1.3). Thus, the thrust is simply $-\dot{m}_g \bar{v}'$. This assumption is equivalent to assuming that the exhaust gases are expanded to the local atmospheric pressure. In any actual case it is customary to experimentally define an "effective" v' which corrects for the existing pressure differential.

Using these assumptions and introducing nomenclature for the magnitude of the thrust and drag

$$T = \dot{m}_g v' \qquad D = F \quad \ldots\ldots [4]$$

Equation [2] can be written in the scaler form

$$T - D = m \frac{dv}{dt} \quad \ldots\ldots [5]$$

In Equation [5], T and m are generally given functions of time (e.g., Equation [3]), while D is a known function of v. Since D varies roughly as v^2, Equation [5] is in general nonlinear (2). However, for the case of constant thrust (T = const), the variables in [5] separate (2), and the equation ingrates immediately. A more convenient form of the solution is obtained, however, if [3, 5] are used together. From [3]

$$\frac{dm}{dt} = -\dot{m}_g$$

may be written; or alternately

$$\frac{dm}{m} = -\frac{\dot{m}_g}{m} dt \quad \ldots\ldots [6]$$

Substituting for m given by [5] into the right-hand member of [6] and noting [4]

$$\frac{dm}{m} = -\frac{\dot{m}_g}{(T - D)\Big/\dfrac{dv}{dt}} dt = -\frac{T}{v'(T - D)} dv \quad \ldots\ldots [7]$$

Received Sept. 3, 1956.

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[3] Numbers in parentheses indicate References at end of paper.

Using the boundary conditions

$$v(t = 0) = v_o$$

$$m(t = 0) = m_o$$

Equation [7] integrates to

$$\ln \frac{m}{m_o} = -\int_{v_o}^{v} \frac{1}{v'} \frac{T}{T - D}\, dv \quad \ldots\ldots [8]$$

For practically all rockets fired in the neighborhood of the earth's surface, v' is essentially constant and [8] may be written

$$\ln \frac{m}{m_o} = -\int_{v_o}^{\nu} \frac{T}{T - D}\, d\nu \quad \ldots\ldots [9]$$

wherein $\nu = v/v'$. Equation [9] describes the motion of the rocket throughout burning.

At the instant burnout occurs, it is noted that

$$m = m_b = m_o - m_p$$

and

$$\nu_b = v_b/v'$$

Thus, [9] becomes

$$\ln \frac{m_o}{m_b} = \int_{\nu_o}^{\nu_b} \frac{T}{T - D}\, d\nu \quad \ldots\ldots [10]$$

Equation [10] is the desired generalization of [1].

For the case of zero drag ($D = 0$), the integration of [10] is trivial and gives immediately

$$\ln \frac{m_o}{m_b} = \nu_b - \nu_o = \frac{v_b}{v'} - \frac{v_o}{v'} \quad \ldots\ldots [11]$$

i.e., Equation [1].

It should be noted that if the drag D is small throughout burning compared to the thrust T, variations in thrust or drag can have only a secondary effect on the burnt velocity. Hence, the burnt velocity would be rather insensitive to any thrust (or drag) characteristic as is well known in the case of [1]. When the drag-to-thrust ratio is small, Equation [10] may be written in the simple form

$$\ln \frac{m_o}{m_b} \simeq \int_{\nu_o}^{\nu_b} \left(1 + \frac{D}{T}\right) d\nu = \nu_b - \nu_o + \int_{\nu_o}^{\nu_b} \frac{D}{T}\, d\nu. \quad [12]$$

which is particularly convenient for estimating the effects of drag or thrust on the mass ratio.

If the thrust is not constant, the variables in Equations [9, 10] are not separated and the integration is not straightforward. There is, however, one special case of nonconstant thrust which is easily integrated. When the *ratio* of drag-to-thrust is constant, the integration of [10] is once again trivial and gives immediately

$$v_b - v_o = \left(1 - \frac{D}{T}\right)_{\text{const}} v' \ln \frac{m_o}{m_b}$$

By using a "constant" average ratio of drag-to-thrust, this case can also be used for estimating the effect of drag or thrust on the mass ratio.

Before considering the practical applications of this analysis some final observations of a general nature can be obtained from [9, 10]. The velocity v (or ν) can increase only when $T > D$. Hence, if T_{max} is the maximum value of the thrust for a given rocket, the velocity corresponding to $D = T_{max}$ is an upper bound to the attainable velocity. This limiting velocity, therefore, depends only upon the maximum thrust and the drag characteristics of the rocket and is independent of the propellant mass to inert mass ratio. Instances of the limiting velocity are given in the following sections.

For constant thrust, the singularity in Equation [9] when $D = T$ is a nonintegrable singularity (3). Hence the condition $D \to T$ corresponds to $m \to 0$ (the inert mass approaching zero) which is an impossible physical condition. Thus for any launching condition other than $D = T$, the rocket cannot subsequently attain the condition $D = T$. However, the launching condition $D = T$ corresponds to a stable solution, $v =$ const, of [5], so that this condition, once given, essentially continues as long as the thrust is maintained. The lauching condition $D < T$ is of principal interest. For this case, the rocket velocity steadily increases until burnout which for any value of $(m_b/m_o) > 0$ must occur before $D = T$.

The drag-free solution, [1], shows that the burnt velocity is independent of the thrust. Equation [10], however, shows that for a fixed mass ratio m_b/m_o, the burnt velocity increases with increasing thrust. In the limiting condition, $T \to \infty$, Equation [10] again reduces to [1], (i.e., the drag-free case) thus indicating the limiting nature of [1]. In the usual rocket motor, an upper limit is imposed on the thrust. Equation [10] shows that for a fixed mass ratio, the maximum achievable burnt velocity will be realized only if this limiting thrust is maintained throughout the burning time. Hence, the constant thrust solution is of primary importance. Furthermore, Equation [10, 12] indicate that the effect of thrust on the burnt velocity is most pronounced when the drag is largest, i.e., near burnout.

Application of the Analysis

For the remainder of this paper, the effect of drag, propellant mass, and inert ("burnt") mass, on the burnt velocity will be studied. In particular, three specific cases of real physical significance are presented:

1 A rocket that burns out before reaching sonic velocity.
2 A rocket that is launched supersonically.
3 A rocket that is launched subsonically and burns out at a supersonic velocity.

In each case:

(a) The thrust T is assumed to be constant so that [10] integrates immediately.

(b) The drag D is represented by

$$D = K_d \rho d^2 v^2 \quad \ldots\ldots [13]$$

wherein K_d is a function of flight Mach number M, and the air density ρ is constant.

(c) At the instant the rocket is launched, the drag is assumed to be less than the thrust so that the velocity of the rocket increases during burning. Although the results are more generally applicable, this assumption simplifies the discussion of the results.

As Equation [9] is of the same functional form as [10], the results give not only the burnt mass to burnt velocity relationship, but more generally the mass-velocity relationship at any instant up to and including burnout.

Before considering the three individual cases, it is convenient to introduce a dimensionless parameter δ defined by

$$\delta^2 = \frac{\rho d^2 v'}{\dot{m}_g} = \frac{\rho d^2 v'^2}{T} \quad \ldots\ldots [14]$$

Using this parameter, the drag may be written

$$D = K_d \delta^2 T \nu^2 \quad \ldots\ldots [15]$$

wherein

$$\nu = \frac{v}{v'} = \frac{M}{M'} \quad \ldots\ldots [16]$$

1 Mach Number at Burnout Less Than Unity

For this case, the drag coefficient is assumed to be constant; i.e.

$$K_d = K_{do} \quad \ldots\ldots [17]$$

and [10] becomes

$$\ln \frac{m_o}{m_b} = \int_{\nu_o}^{\nu_b} \frac{d\nu}{1 - K_{do}\delta^2\nu^2} \quad \ldots\ldots\ldots [18]$$

which yields upon integration

$$\frac{m_o}{m_b} = \left[\left(\frac{1 + \delta\sqrt{K_{do}}\,\nu_b}{1 - \delta\sqrt{K_{do}}\,\nu_b}\right)\left(\frac{1 - \delta\sqrt{K_{do}}\,\nu_o}{1 + \delta\sqrt{K_{do}}\,\nu_o}\right)\right]^{\frac{1}{2\delta\sqrt{K_{do}}}} \quad [19]$$

The maximum value of ν_b is given by [19] as

$$\nu_b \leq \frac{1}{\delta\sqrt{K_{do}}} \quad \ldots\ldots\ldots [20]$$

From [15, 17], it is seen that the quantity $(K_{do}\delta^2\nu_b^2)$ is the ratio of the drag-to-thrust at burnout, which according to [20] is always less than unity.

A somewhat more general form of [19] can be had by a simple arrangement, i.e.

$$\left(\frac{m_b}{m_o}\right)^{2\delta\sqrt{K_{do}}} \cdot F = \left(\frac{1 - \delta\sqrt{K_{do}}\,\nu_b}{1 + \delta\sqrt{K_{do}}\,\nu_b}\right) \quad \ldots\ldots [21]$$

wherein F is defined by

$$F(\delta\sqrt{K_{do}}\,\nu_o) = \frac{1 - \delta\sqrt{K_{do}}\,\nu_o}{1 + \delta\sqrt{K_{do}}\,\nu_o} \quad \ldots\ldots\ldots [22]$$

This form of the equation is particularly convenient since the function F separates out the effect of the launching velocity. It should be noted that for zero launching velocity, $F = 1$, and that F decreases with increasing ν_o. Thus, in a sense, F is a measure of the reduction in propellant required to achieve a given velocity if an outside launching agency is used.

A graph of Equation [21] is shown in Fig. 1. The curve is nothing more than the simple function

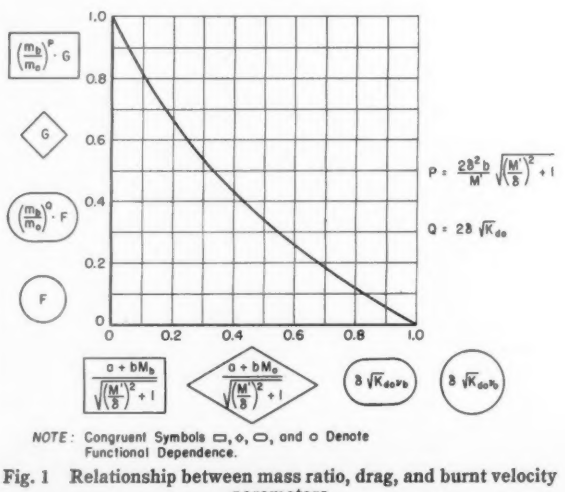
$$y = \frac{1 - x}{1 + x} \quad \ldots\ldots\ldots [23]$$

for $0 \leq x \leq 1$. It should be noted that Equations [21, 22] are both of this form. The additional nomenclature shown in Fig. 1 will be explained in the following sections.

2 Mach Number at Launching Greater Than Unity

For this case, the drag coefficient is assumed to decrease with increasing Mach number. R. N. Thomas of the Ballistic Research Laboratories has found (4,5) that the supersonic drag coefficient for a number of sharp-pointed, square-based projectiles can be correlated with an equation of the form

$$K_d = b^2 + \frac{2ab}{M} + \frac{(a^2 - 1)}{M^2} \quad \ldots\ldots\ldots [24]$$



NOTE: Congruent Symbols □, ◇, ⬭, and ○ Denote Functional Dependence.

Fig. 1 Relationship between mass ratio, drag, and burnt velocity parameters

TYPE		a	b	
J_2	5° BOAT-TAIL 7° BOAT-TAIL	0.9575 ±0.0077 0.9536 ±0.0047	0.1263 ±0.0039 0.1271 ±0.0027	M > 1.0
J_3		0.8066	0.2894	M > 1.0
J_4		0.8624	0.2207	M > 1.0
J_5	75 MM MK IV 3.3" MK II	0.8780 ±0.0081 0.8177 ±0.0139	0.1970 ±0.0044 0.2424 ±0.0069	M > 1.0
J_6		0.9460	0.1464	M > 1.0

SHELL SHAPES

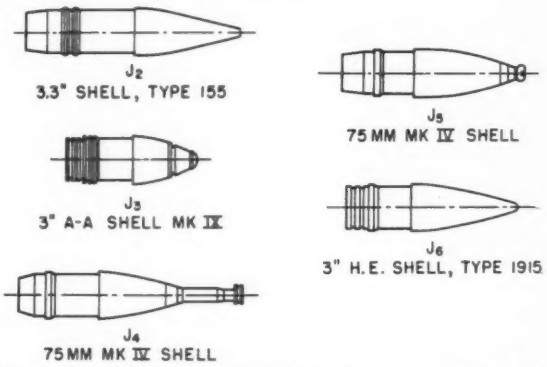


Fig. 2 Empirical drag—constants and corresponding shell shapes

wherein a and b are empirical constants. Fig. 2, taken from Thomas' report (5), shows several projectile shapes and the corresponding values of a and b.

Assuming that Equation [24] can also be used to represent the drag coefficient Mach number relationship of a burning rocket, the computation of the burnt mass-burnt velocity relationship once again becomes a routine integration.

Thus, using Equations [24, 15, and 10] in turn

$$\ln \frac{m_o}{m_b} = \int_{\nu_c}^{\nu_b} \frac{d\nu}{1 - \delta^2\left[b^2\nu^2 + \frac{2ab}{M'}\nu + \frac{a^2 - 1}{M'^2}\right]} \quad [25]$$

wherein $M' = \nu'/C$. Integration of [25] yields

$$\frac{m_o}{m_b} = \left[\frac{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1} + (a + bM_b)}{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1} - (a + bM_b)} \cdot \frac{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1} - (a + bM_o)}{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1} + (a + bM_o)}\right]^{\frac{M'}{2\delta^2 b\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1}}} \quad \ldots\ldots [26]$$

Equation [26] gives the burnt mass-burnt velocity relationship for a rocket having a drag coefficient Mach number dependency given by [24].

As in case 1, the maximum value of M_b is given by [26] as

$$M_b \leq \frac{1}{b}\left(\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1} - a\right) \quad \ldots\ldots\ldots [27]$$

However, in this case the ratio of drag-to-thrust at burnout is somewhat more complicated, and —noting Equations [15, 24]—given by

$$\frac{D_b}{T} = \left(\frac{\delta}{M'}\right)^2\left[M_b^2\left(b^2 + \frac{2ab}{M_b} + \frac{a^2 - 1}{M_b^2}\right)\right]$$

This quantity differs from unity by

$$1 - \frac{D_b}{T} = \left(\frac{\delta}{M'}\right)^2 \left[\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1} - (a + bM_b)\right] \cdot \ldots \left[\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1} + (a + bM_b)\right]$$

which by Equation [27] is always positive; i.e., the ratio of drag-to-thrust at burnout is always less than unity. Rearranging, as in Case 1, Equation [26] may be written in the form

$$\left(\frac{m_b}{m_o}\right)^{\frac{2\delta^2 b\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1}}{M'}} \cdot G = \frac{1 - \frac{a + bM_b}{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1}}}{1 + \frac{a + bM_b}{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1}}} \quad [28]$$

wherein the function G is defined by

$$G = \frac{1 - \frac{a + bM_o}{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1}}}{1 + \frac{a + bM_o}{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1}}} \quad [29]$$

Once again, Equations [28, 29] are both of the general form given in [23] and plotted in Fig. 1. Hence, this graph, as is indicated on the axes, is sufficient not only for the purely subsonic case (Equations [21, 22]) but also for the supersonic case as well (Equations [28, 29]).

3 Subsonic Launching Velocity, Supersonic Burnout Velocity

The solution in case 3 is a combination of the results of cases 1 and 2. Throughout the subsonic region, the drag coefficient is assumed to be given by [17] (i.e., a constant). At Mach 1, the coefficient is assumed to display a finite jump and subsequently (in the supersonic region)to obey the Mach number dependence given by [24]. Thus, Equation [10] becomes

$$\ln \frac{m_o}{m_b} = \int_{v_o}^{1/M'} \frac{dv}{1 - K_d \delta^2 v^2} + \int_{1/M'}^{v_b} \frac{dv}{1 - \delta^2\left[b^2v^2 + \frac{2ab}{M'}v + \frac{a^2 - 1}{M'^2}\right]} \quad [30]$$

wherein the limits $1/M'$ correspond to Mach 1. Integration of [30] yields

$$\frac{m_o}{m_b} = \left[\frac{1 + \frac{\delta\sqrt{K_{do}}}{M'}}{1 - \frac{\delta\sqrt{K_{do}}}{M'}} \cdot \frac{1 - \frac{\delta\sqrt{K_{do}}}{M'}M_o}{1 + \frac{\delta\sqrt{K_{do}}}{M'}M_o}\right]^{\frac{1}{2\delta\sqrt{K_{do}}}} \cdot \left[\frac{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1} + (a + bM_b)}{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1} - (a + bM_b)}\right] \cdot \left[\frac{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1} - (a + b)}{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1} + (a + b)}\right]^{\frac{M'}{2\delta^2 b\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1}}} \quad [31]$$

From this equation it is seen that if supersonic flight does occur, the Mach number at burnout M_b is limited by

$$M_b \leq \frac{1}{b}\left[\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1} - a\right] \quad [32]$$

which is the same as for case 2. According to [31], supersonic flight will occur only if the condition

$$\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1} > a + b$$

or

$$\left(\frac{M'}{\delta}\right)^2 > b^2 + 2ab + a^2 - 1 \quad [33]$$

is realized. The inequality simply states (see [14, 4, 24]) that the thrust must be greater than the drag in the initial portion of the supersonic region. Since, however, the drag coefficient has a finite jump at Mach 1, the rocket can conceivably attain flight Mach 1 and still violate this condition. This violation can occur and Mach 1 still be realized (according to [31]) if

$$\frac{\delta\sqrt{K_{do}}}{M'} < 1$$

or

$$\left(\frac{M'}{\delta}\right)^2 > K_{do} \quad [34]$$

Hence, noting Equations [33, 34], if the inequalities

$$K_{do} < \left(\frac{M'}{\delta}\right)^2 < b^2 + 2ab + a^2 - 1 \quad [35]$$

are satisfied, the rocket will become "stuck" at Mach 1. If, then, the rocket is launched subsonically, it cannot proceed supersonically. Equation [35] therefore defines a realistic "sonic barrier" in such (rather unusual) cases.

Finally, it should be noted that the left side of [31] may be written in the form

$$\left(\frac{m_o}{m_b}\right)_{\text{subsonic-to-supersonic}} = \left(\frac{m_o}{m_b}\right)_{\text{subsonic-to-sonic}} \cdot \left(\frac{m_o}{m_b}\right)_{\text{sonic-to-supersonic}} \quad [36]$$

wherein the two factors on the right are given by cases 1 and 2 with appropriate interpretations of the respective mass ratios. For the factor $(m_o/m_b)_{\text{subsonic-to-sonic}}$, m_o is the actual mass of the rocket at the subsonic launching velocity while m_b becomes the "apparent" burnt mass of the rocket given by [19] when evaluated at Mach 1. In the factor $(m_o/m_b)_{\text{sonic-to-supersonic}}$, m_o becomes the "apparent" initial mass of the rocket at Mach 1 and hence is equal to the "apparent" burnt mass above; m_b is the actual burnt mass of the rocket at the supersonic burnt velocity. The left-hand member of [36] is the actual initial mass to burnt mass ratio. With this interpretation of the mass ratios, this case is nothing more than the product of cases 1 and 2. Thus Fig. 1, a graph of the simple function $y = (1 - x)/(1 + x)$ for $0 \leq x \leq 1$, is the canonical form of the solution.

Computations

Although Fig. 1 is of theoretical interest, it is not particularly convenient for computations. The objectionable character of this graph lies in the nonlinear appearance of the mass ratio in the ordinate. This nonlinearity also detracts from the value of the plot as a graphic representation of the relationships. A more convenient and graphic form may be obtained as follows:

Introducing the transformations

$$\Psi_o = \frac{a + bM_o}{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1}}$$

$$\Psi_b = \frac{a + bM_b}{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1}} \quad \text{.....[37]}$$

into Equations [28, 29, 31], Equations [21, 22, 28, 29, and 31] may be written

$$\frac{m_b}{m_o} \cdot (F)^{1/Q} = \left(\frac{1 - \delta\sqrt{K_{do}}\, v_b}{1 + \delta\sqrt{K_{do}}\, v_b}\right)^{1/Q} \quad \text{.....[21a]}$$

$$(F)^{1/Q} = \left(\frac{1 - \delta\sqrt{K_{do}}\, v_o}{1 + \delta\sqrt{K_{do}}\, v_o}\right)^{1/Q} \quad \text{.....[22a]}$$

$$\frac{m_b}{m_o} \cdot (G)^{1/P} = \left(\frac{1 - \Psi_b}{1 + \Psi_b}\right)^{1/P} \quad \text{.....[28a]}$$

$$(G)^{1/P} = \left(\frac{1 - \Psi_o}{1 + \Psi_o}\right)^{1/P} \quad \text{.....[29a]}$$

$$\frac{m_b}{m_o}\left[\frac{F}{F\left(v_o = \frac{1}{M'}\right)}\right]^{1/Q}\left[G\left(\Psi_o = \frac{a + b}{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1}}\right)\right]^{1/P} = \left(\frac{1 - \Psi_b}{1 + \Psi_b}\right)^{1/P} \quad \text{.....[31a]}$$

wherein the nomenclature

$$P = \frac{2\delta^2 b\sqrt{(M'/\delta)^2 + 1}}{M'} \qquad Q = 2\delta\sqrt{K_{do}} \quad \text{.....[38]}$$

has been introduced for conciseness. It should then be noted that the functional form of the right-hand members of [21a, 22a, 28a, 29a, 31a] is the same and, furthermore, that the mass ratios now appear linearly in all three cases. A plot of this common functional form

$$y = \left(\frac{1 - x}{1 + x}\right)^{1/R}$$

is sufficient for all computations. In Fig. 3, the left-hand members of [21a, 22a, 28a, 29a, 31a] appear as functions of the four quantities $\delta\sqrt{K_{do}}\, v_b$, $\delta\sqrt{K_{do}}\, v_o$, Ψ_b, and Ψ_o, respectively, for representative values of $1/R = (1/P), (1/Q)$.

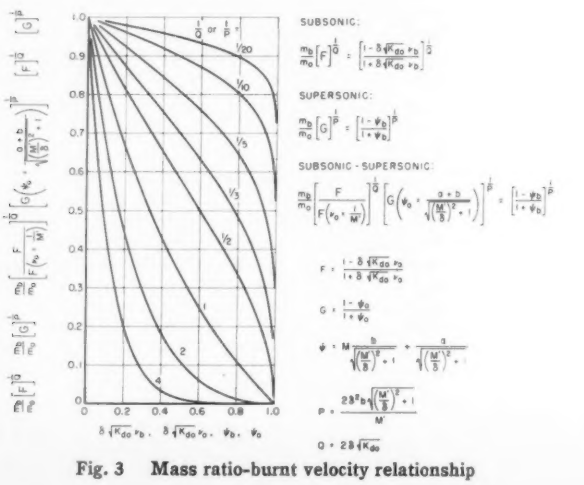


Fig. 3 Mass ratio-burnt velocity relationship

As an example of the use of this figure, the following problem is considered. It is desired to design a 3-in., 1000-lb thrust rocket to be launched at 700 fps and burning out at 2500 fps. It is estimated that $v' = 6440$ (specific impulse o 200 sec) and that $a = 0.87$, $b = 0.20$, $K_{do} = 0.09$ (see Fig. 2) are realistic values. From these quantities the following values are computed

$$\Psi_b = 0.522$$

$$\Psi_o = \frac{a + b}{\sqrt{\frac{M'^2}{\delta} + 1}} = 0.404$$

$$1/Q = 0.674$$

$$1/P = 0.926$$

$$\delta\sqrt{K_{do}}\, v_o = 0.081$$

$$\delta\sqrt{K_{do}}\,(1/M') = 0.129$$

Entering Fig. 3, the following quantities are read in quick succession

$$\frac{m_b}{m_o}\left[\frac{F}{F(v_o = 1/M')}\right]^{1/Q}\left[G\left(\Psi_o = \frac{a + b}{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1}}\right)\right]^{1/P} = 0.34 \quad \text{.....[a]}$$

$$\left[G\left(\Psi_o = \frac{a + b}{\sqrt{\left(\frac{M'}{\delta}\right)^2 + 1}}\right)\right]^{1/P} = 0.43 \quad \text{.....[b]}$$

$$[F(v_o = 1/M')]^{1/Q} = 0.84 \quad \text{.....[c]}$$

$$[F]^{1/Q} = 0.89 \quad \text{.....[d]}$$

Substituting the values given by [b, c, d] into [a] gives $m_b/m_o = 0.75$. This ratio does not differ significantly from the value 0.755 given by [1] (the drag free solution). Appreciable effects on the mass ratio are noted, however, if the thrust of the rocket is decreased. Performing the above calculation for several values of thrust gives the results shown in Table 1. It is of some interest to compare these data with the same quantities computed for an otherwise identical rocket launched at 1200 fps and burning out at 3000 fps, i.e., the same increase in velocity as those projectiles in Table 1 but flying in a higher velocity region. This computation gives the results shown in Table 2.

Table 1

$d = 3$ in., $v_o = 700$ fps, $v_b = 2500$ fps, $v' = 6440$ fps

Thrust T, lb	Mass ratio m_b/m_o	Drag-to-thrust ratio at burnout D_b/T
∞	0.755	0
1000	0.75	0.137
500	0.72	0.274
250	0.67	0.549

Table 2

$v_o = 1200$, $v_b = 3000$

Thrust T, lb	Mass ratio m_b/m_o	Drag-to-thrust ratio at burnout D_b/T
∞	0.755	0
1000	0.74	0.172
500	0.71	0.343
250	0.61	0.687

(*Continued on page 168*)

On the Development of Rational Scaling Procedures for Liquid-Fuel Rocket Engines[1]

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A critical summary is presented of recent theoretical studies concerning similarity analysis and the scaling of liquid-fuel rocket engines. On the basis of this work, some suggestions are offered for an experimental program which has as its objective the development of rational scaling procedures.

I Introduction

THE construction of large liquid-fuel rocket engines has been hampered by the necessity of full-scale engine development programs. The experimental difficulties encountered with engines of different sizes are perhaps best illustrated by the occurrence of uncontrolled combustion oscillations, which are sometimes minimized or eliminated by artistic variations in injector design based on previous encounters with similar problems (1).[3] In a survey paper concerned with experimental aspects of the rocket engine development program, Ross (2) has recently summarized the sort of concepts current among designers. Crocco (3) and Penner (4), commenting on this work, conclude that the science of engine scaling is still in an early phase of development.

During the last two years a concerted effort has been made to define the problem of engine scaling in scientific terms. Thus the important similarity parameters have been obtained (5) and shown to include the same dimensionless groups which are required for flow systems without chemical reactions, as well as two of the five similarity groups considered by Damköhler (6) in a classical paper on the scaling of chemical reactors. The dimensionless groups which must be maintained invariant in the scaling of chemical reactors (of which liquid-fuel rocket engines constitute a special class) are summarized in Section IIA.

Following Damköhler's procedure for chemical reactors, the problem of scaling for the steady internal aerothermochemistry of liquid-fuel rocket engines has been formulated (5). The method was then developed into an exact prescription for engine scaling on the assumption that the rocket combustion chamber may be considered to be a stirred reactor (7). The resulting scaling procedure may be shown to be consistent with a microscopic analysis of the combustion reactions, based on the assumption that the mass burning rate of the droplets is a linear function of the effective droplet diameter. Control over chemical conversion rate, which is essential for engine scaling with maintenance of exact similarity, is supposed to be obtained by control of droplet size, for example, through variation of the surface tension by the addition of suitable surface-active agents. Following Crocco's terminology (3), we shall refer to this scaling procedure as the P-T (Penner-Tsien) method. It is evident from the preceding remarks, relating to the physical model on which the P-T technique is based, that successful scaling of engines by this method can be accomplished only for bipropellant systems with greatly different volatilities (e.g., LOX − JP4 or HNO_3 − NH_3).

The next important theoretical development is due to Crocco (3), who has succeeded in developing a rational scaling procedure for the steady operation and for high-frequency oscillations in the special case in which the chemical conversion time varies inversely with the first power of the pressure. This basic requirement may conceivably be met in practice for rocket motors in which the ignition time is long compared to the reaction time (i.e., particularly for nonhypergolic mixtures at relatively low pressures).

Engine development on the basis of the P-T model involves small-scale tests with motors utilizing very high injection velocities and fine sprays for the less volatile component. On the other hand, the procedure of Crocco requires model testing in rocket chambers operating at very high pressures.

We present in Section II a critical survey of theoretical studies related to the scaling of liquid-fuel rocket engines. In Section III we present some remarks on the development of an experimental program which is designed to furnish the needed basic data for the rational scaling of liquid-fuel rocket engines.

II Outline of Theoretical Studies

We present in Section IIA a list of similarity parameters. Section IIB is devoted to a general formulation of engine scaling procedures. In Sections IIC and IID we consider, respectively, the development of the P-T and Crocco rules. Included in Section IIC is a very simple argument due to Theodore von Kármán which is based on the idea that high-frequency oscillations can be avoided in large engines by maintaining the coupling between chemical and oscillation times at the same level as in a well-performing prototype, irrespective, for example, of the maintenance of similarity for the steady aerothermochemistry of motor operation.

A Similarity Parameters for the Steady Aerothermochemistry of Motor Operation[4]

Scaling criteria for homogeneous and heterogeneous chemical reactors may be obtained from the conservation equations for reacting gas mixtures. The complete set of similarity parameters has been shown to include the following dimensionless groups (5)

$$\text{Reynolds number} = Re = \rho_o v_o L/\eta_o \quad [1]$$

$$\text{Schmidt number} = Sc = \eta_o/\rho_o D_o \quad [2]$$

$$\text{Prandtl number} = Pr = c_{p,o}\eta_o/\lambda_o \quad [3]$$

$$\text{Mach number} = M = \sqrt{\rho_o v_o^2/\gamma_o p_o} \quad [4]$$

Presented at the ARS Fall Meeting, Buffalo, N. Y., Sept. 24–26, 1956.

[1] The work described in this paper was supported by the U. S. Air Force, Office for Advanced Study, under Contract AF 18(603)-107 with the American Machine and Foundry Company and Jet Propulsion Research, Inc.

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[3] Numbers in parentheses indicate References at end of paper.

[4] See Reference (7).

$$\text{Froude number} = Fr = v_o^2/gL \quad [5]$$

$$\text{Damköhler's first similarity group} = \mathrm{D_I} = (L/v_o)/t_i \quad [6]$$

$$\text{Damköhler's third similarity group} = \mathrm{D_{III}} = q'L/v_o c_{p,o}\vartheta_o t_i \quad [7]$$

$$\varphi = \tfrac{1}{2}v_o^2/(c_{p,o}/\gamma_o)\vartheta_o \quad [8]$$

and

$$\gamma_o = c_{p,o}/c_{v,o} \quad [9]$$

Here ρ = density, v = linear flow velocity, L = a composite designation for all important lengths, η = viscosity coefficient, D = diffusion coefficient, c_p = specific heat at constant pressure, λ = thermal conductivity, γ = ratio of the specific heat at constant pressure (c_p) to the specific heat at constant volume (c_v), g = constant gravitational acceleration, t_i = characteristic conversion time of an important chemical species (e.g., of reaction product),[5] q' = standard specific enthalpy difference between reaction products and reactants, ϑ = temperature of the gas mixture; the subscript o identifies suitably selected upstream reference conditions.

The characteristic conversion or reaction time t_i is defined by the relation

$$t_i = \rho Y_i/w_i \quad [10]$$

where w_i represents the net rate of mass change per unit volume produced by chemical reaction of the important chemical species i, and Y_i denotes the corresponding weight or mass fraction. The parameter $\mathrm{D_I}$ measures the ratio of the rate of change of i, produced by chemical reaction, to the rate of change of i produced by convection. Similarly, $\mathrm{D_{III}}$ expresses the ratio of the rate of heat addition resulting from chemical reaction to the rate of heat addition associated with enthalpy flux by convection.

For low velocity flow problems involving fixed chemical reactants in the absence of external forces, results equivalent to Damköhler's (6) five similarity criteria are obtained (viz., only [1, 2, 3, 6, and 7] must remain invariant in order to maintain thermal, dynamic, and reaction kinetic similarity). Maintenance of complete chemical and reaction kinetic similarity in the gas stream automatically satisfies the boundary conditions for heat transfer to the chamber walls (i.e., the Nusselt heat transfer number is constant for fixed values of the Reynolds and Prandtl numbers) except in the case where surface-catalyzed chemical reactions play an important role. For surface-catalyzed reactions the boundary conditions remain similar if two new groups, analogous to those described by Equations [6, 7], are introduced for the important chemical species reacting at the wall.

Our present state of ignorance concerning engine scaling is such that we do not know whether or not maintenance of constant Mach number is important. For this reason we shall follow Crocco (3) in treating scaling separately without consideration of M (P-T rule and Crocco's second rule) and scaling for fixed M without consideration of $\mathrm{D_I}$ or $\mathrm{D_{III}}$ (Crocco's first rule). All of our discussion will be restricted to a fixed bipropellant mixture which is to be injected at the same temperature in both model (identified by the subscript Mo) and large-scale (identified by the subscript H for "Hauptausführung") experiments. The P-T and Crocco rules were developed without explicit reference to bipropellant systems. Since it may be instructive to focus attention on the physical variables involved, we utilize in Sections IIB and IIC a modified approach in which the special features of bipropellant operation are emphasized.

[5] The use of a single characteristic reaction time involves the implicit assumption that it is sufficient to restrict the discussion to consideration of the single chemical species i. This assumption appears to be justified for the following reason: If the physical states of two systems are similar, and if the time history of the important chemical species i (e.g., of reaction product) is similar, then the entire complicated reaction scheme in the two systems will be similar.

B Formulation of Scaling Procedure for a Bipropellant Rocket Engine (Variable Mach Number)

Consider a cylindrical bipropellant liquid-fuel rocket engine of length l and diameter d. The chamber has a plane injection plate with regularly spaced injection orifices. The distance between fuel orifices is d_F, between oxidizer orifices d_O, and between fuel and oxidizer orifices d_{FO}. The fuel orifice diameter is h_F and the oxidizer orifice diameter is h_O. Let N_F and N_O denote, respectively, the number of fuel and oxidizer injection orifices. Also v_F and v_O represent the corresponding fuel and oxidizer injection velocities.

The total mass flow rate in the large motor H will be n times the flow rate in the model Mo if

$$\frac{(v_O h_O^2 N_O)_H}{(v_O h_O^2 N_O)_{Mo}} = \frac{(v_F h_F^2 N_F)_H}{(v_F h_F^2 N_F)_{Mo}} = n \quad [11]$$

The quantity n is thus the thrust ratio of the large motor H with respect to the model Mo.

For a given propellant system with fixed physicochemical parameters and for either fixed or variable chamber pressure, constancy of Pr and Sc is assured. Furthermore, q' is fixed and, for the same injection temperature, φ_o is also fixed; therefore, constancy of $\mathrm{D_{III}}$ is implied by constancy of $\mathrm{D_I}$. The parameter γ remains invariant and φ is unimportant for small values of v_o. The Froude and Mach numbers will be ignored on the assumption that we are dealing with a low velocity flow problem in which acceleration effects are unimportant. The scaling requirements for fixed Mach number will be considered in Section IID. It is apparent that maintenance of exact similarity for the steady aerothermochemistry, subject to the previously noted simplifying assumptions, now requires only enforcement of the conditions of geometric similarity, of fixed Re and of fixed $\mathrm{D_I}$.

The requirements for geometric similarity of the chamber are

$$\frac{L_H}{L_{Mo}} = \frac{(d_F)_H}{(d_F)_{Mo}} = \frac{(d_O)_H}{(d_O)_{Mo}} = \frac{d_H}{d_{Mo}} = \frac{(d_{FO})_H}{(d_{FO})_{Mo}} = \frac{l_H}{l_{Mo}} = n' \quad [12]$$

if the injector orifice diameters are small compared with all of the other important dimensions. Furthermore, if all of the distances are scaled in proportion, then the number of injection orifices is fixed, i.e.

$$\frac{(N_O)_H}{(N_O)_{Mo}} = \frac{(N_F)_H}{(N_F)_{Mo}} = 1$$

Therefore, the over-all thrust relation given in Equation [11] becomes simply

$$\frac{(v_O h_O^2)_H}{(v_O h_O^2)_{Mo}} = \frac{(v_F h_F^2)_H}{(v_F h_F^2)_{Mo}} = n \quad [13]$$

Constant Re will be maintained with respect to all chamber dimensions if

$$(\rho_o v_o L)_H = (\rho_o v_o L)_{Mo} \quad [14]$$

since η_o is fixed. Here v_o represents either v_F or v_O and L is a composite designation for all chamber lengths. Finally, chemical similarity is maintained if

$$(L/v_o t_i)_H = (L/v_o t_i)_{Mo} \quad [15]$$

C Development of the P-T Rule (Fixed Chamber Pressure)

For fixed chamber pressure, ρ_o is constant, since the injection temperature ϑ_o has already been specified. There-

fore, Equations [12, 13, 14, 15] may be combined to yield the relations

$$\frac{(v_o)_H}{(v_o)_{Mo}} = \frac{(v_F)_H}{(v_F)_{Mo}} = \frac{(v_O)_H}{(v_O)_{Mo}} = \frac{1}{n'} \quad [16]$$

$$\frac{(h_F{}^2)_H}{(h_F{}^2)_{Mo}} = \frac{(h_O{}^2)_H}{(h_O{}^2)_{Mo}} = n'n \quad [17]$$

$$\frac{(t_i)_H}{(t_i)_{Mo}} = (n')^2 \quad [18]$$

It has been emphasized previously (7) that a more detailed prescription for rational motor scaling requires experimental determination of t_i as a function of injector design, and of the physicochemical parameters affecting the problem, before Equations [16–18] can be used for the determination of the relation between n and n'. In the absence of quantitative information concerning the functional form of t_i, it is nevertheless of interest to illustrate the method of analysis by a simple example based on an oversimplified picture of the combustion processes.

1 Maintenance of Similarity for Steady Operation With Uniform Combustion Throughout the Chamber Volume

Observations of the interior of some rocket combustion chambers during operation show that the hot gases are under strong agitation and turbulence with eddy sizes of the order of the chamber dimensions. Hence it is reasonable to approximate these combustion chambers as homogeneous reactors. The mass rate of conversion w_i of propellant for steady burning per unit volume is then equal to mass of propellant injected per unit time, divided by the volume of the combustion chamber, i.e.

$$w_i \propto \frac{\rho_O v_O h_O{}^2 N_O}{ld^2} \propto \frac{\rho_F v_F h_F{}^2 N_F}{ld^2} \propto \frac{\rho_o v_o h^2 N}{ld^2} \quad [19]$$

Since combustion occurs uniformly throughout the chamber volume, it follows that

$$t_i = \frac{\rho_o Y_{i.o}}{w_i} \propto \frac{ld^2 Y_{i.o}}{v_o h^2 N}$$

or, since $Y_{i.o}$ is fixed

$$\frac{(t_i)_H}{(t_i)_{Mo}} = \frac{(ld^2)_H}{(ld^2)_{Mo}} \frac{(v_o h^2 N)_{Mo}}{(v_o h^2 N)_H} \quad [20]$$

Introduction of Equations [11, 12, and 18] into Equation [20] leads to the result

$$(n')^2 = (n')^3 (1/n)$$

or

$$n' = n \quad [21]$$

In view of Equation [21] we now obtain the following basic results for maintenance of exact similarity with respect to the steady aerothermochemistry of internal motor operation (P-T rule)

$$(p)_H = (p)_{Mo} \qquad (\vartheta_o)_H = (\vartheta_o)_{Mo}$$

$$\frac{(v_o)_H}{(v_o)_{Mo}} = \frac{(v_F)_H}{(v_F)_{Mo}} = \frac{(v_O)_H}{(v_O)_{Mo}} = \frac{1}{n}$$

$$\frac{L_H}{L_{Mo}} \equiv \frac{d_H}{d_{Mo}} \equiv \frac{(d_F)_H}{(d_F)_{Mo}} = \frac{(d_O)_H}{(d_O)_{Mo}} = \frac{(d_{FO})_H}{(d_{FO})_{Mo}} =$$

$$\frac{l_H}{l_{Mo}} = \frac{(h_F)_H}{(h_F)_{Mo}} = \frac{(h_O)_H}{(h_O)_{Mo}} = n$$

$$\frac{(t_i)_H}{(t_i)_{Mo}} = n^2$$

According to the results summarized by the P-T rule, model tests should be made under the same pressure and temperature conditions as are required in the large engine. However, the injection velocity must be higher in the model than in the large engine by the factor n; all linear dimensions (including orifice spacing and orifice diameter) in the large engine must be increased in proportion to the desired thrust increase n; the time for conversion to reaction products must be increased by the factor n^2 in going from the model to the large engine.

It is apparent that the success of the entire scaling procedure rests on our ability to increase the characteristic reaction time proportionately with the square of the engine thrust. In this connection, we may ask whether the over-all considerations leading to the P-T rule are consistent, for example, with the idea that the mass burning rate of a less volatile fuel (such as JP4 in a JP4-LOX mixture) is a linear function of the effective average droplet diameter $\bar{D}$. Here $\bar{D}$ is, in general, a function of the pressure drop across the injector orifices, of orifice diameter, and of the properties of the injected material. However, for heterogeneous diffusion flames in which the mass burning rate is a linear function of drop diameter, it is well known that the basic burning rate expression is

$$\bar{D}_t{}^2 = \bar{D}^2 - K't \quad [22]$$

where $\bar{D}_t$ is the drop diameter at time t if the initial drop diameter is $\bar{D}$, and K' represents the evaporation constant. From Equation [22] it is apparent that the residence time t_r in the chamber, corresponding to $\bar{D}_t = 0$, is

$$t_r \propto \bar{D}^2 \quad [23]$$

We now identify the conversion time t_i with the residence time t_r in a well-designed engine for combustion processes controlled by heterogeneous diffusion flames. It then follows from Equations [18, 21, 23] that

$$(\bar{D})_H/(\bar{D})_{Mo} = n' = n \quad [24]$$

that is, the drop diameter for the assumed burning law specified by Equation [22] must be increased linearly with motor thrust. The desired control over droplet size may possibly be achieved by physicochemical methods (e.g., lowering of surface and interfacial tension) and is consistent with the idea of utilizing higher injection velocities in the model than in the large motor.

It is of interest to note that the P-T rule implies the relation $t_i \sim 1/\Delta p$, where Δp is the pressure drop across the injector orifice. This result follows directly from Equations [16, 23, 24] if $v_o{}^2 \sim \Delta p$.

2 Similarity of High-Frequency Oscillations

We have no practical experience in evaluating the importance of maintaining similarity with respect to high-frequency oscillations either for engines which have or have not been properly scaled with respect to steady motor operation. There appear to be three possible points of view with regard to this problem. These are:

1 High-frequency oscillations will not develop if scaling has been done properly for steady motor operation.

2 Scaling should be done properly for steady operation but there will be sufficient intrinsic perturbations to produce instability. It is therefore important to scale with maintenance of a constant ratio of the chemical time t_i to a wave propagation time t_w. Unstable motor operation is the result of coupling between the chemical and wave propagation times. We must maintain synchronization between reaction and wave propagation processes below a fixed level. This result can presumably be achieved by fixing the ratio t_i/t_w in H at the same value as in Mo where no undesirable chamber oscillations occurred.

3 Scaling with maintenance of similarity for steady motor operation is unimportant. In order to prevent undesirable

chamber oscillations it is only necessary to maintain the ratio t_i/t_w invariant in going from a well-performing model to a large engine.

Implicit in the first point of view is the idea that similitude of the damping effects is sufficient to assure the absence of high-frequency oscillations. The damping effects, in turn, should be largely dependent on the value of *Re* (which remains constant) and on the chemical evolution of the combustion processes (which is determined by D_I). Implicit in the third point of view is the notion that similitude of the driving forces for oscillations is the determining factor and that the damping processes are generally of similar intensity. Finally, the second point of view is based on the idea that high-frequency instability can be avoided only if the driving and damping forces for oscillations are maintained similar.

Depending on the point of view adopted, the P-T rule either is or is not useful since it is easily shown that the ratio t_i/t_w does not remain constant. We proceed to demonstrate this fact on the basis of an analysis proposed independently by von Kármán and by Crocco (3).

For diffusion-controlled processes the conversion time has been shown to be proportional to the square of the scale factor for engine thrust. Thus

$$\frac{(t_i)_H}{(t_i)_{Mo}} \propto n^2$$

On the other hand, t_w is directly proportional to the geometric scale factor $n' = n$ for constant sound velocity, i.e.

$$\frac{(t_w)_H}{(t_w)_{Mo}} \propto n \qquad [25]$$

Comparison of the preceding two relations shows immediately that t_i and t_w are not proportional for scaling according to the P-T rule. In other words, scaling according to the P-T rule does not involve maintenance of similarity for possible high-frequency nonsteady motor operation.

It is a simple matter to obtain scaling criteria if the third of the points of view listed previously is adopted. For example, if heterogeneous gas-liquid diffusion flames are rate-controlling, then the relation

$$t_i/t_w = \text{const}$$

leads to the requirement that

$$t_i = t_r \propto n'$$

i.e., in view of Equation [23]

$$\bar{D} \propto \sqrt{n'} \qquad [26]$$

In other words, the average droplet size for the low volatility component (e.g., JP4 in a JP4-LOX system) in a bipropellant engine should be scaled as the square root of the dimensions in order to maintain a fixed ratio t_i/t_w. As long as Equation [26] is satisfied it does not matter presumably how the other design variables are adjusted.

On the basis of the third point of view described above, Theodore von Kármán has suggested another scaling procedure, which may conceivably be applicable to bipropellant systems in which the fuel and oxidizer have similar volatilities (e.g., RFNA-AN). For processes of this type

$$t_i \propto \frac{d_{FO}^2}{D^*} \qquad [27]$$

where D^* is a suitably selected (binary) diffusion coefficient. On the other hand, for the high-frequency tangential mode of oscillation

$$t_w \propto \frac{d}{a} \qquad [28]$$

where a is the sound velocity. Hence, at constant pressure, the ratio t_i/t_w will remain invariant if

$$d_{FO} \propto \sqrt{d}$$

i.e., if the distance between fuel and oxidizer orifices is scaled as the square root of the chamber diameter.

It is evident that one of the important problems which must be answered by an experimental program for engine scaling procedures is which of the points of view 1 to 3 is the correct one. Perhaps the first investigations should be designed to check the sufficiency or insufficiency of scaling merely with maintenance of constant ratios t_i/t_w. Although this method of approach requires an assumption about t_i, it is a relatively simple matter to test the scaling rules described in Equations [26, 28] for special motors in which the assumed rate-controlling reaction steps probably apply.

3 Similarity of Cooling System, Low-Frequency Oscillations, and Nozzle Design

Crocco (3) has considered the design restrictions arising if similarity is maintained with respect to the cooling system, low-frequency oscillations, and nozzle design. His work is summarized in the next section in so far as it applies to the Crocco and P-T scaling procedures.

D Crocco's Analysis of Engine Scaling

In the discussions presented in the preceding Sections IIB and IIC we have emphasized the relation between scaling parameters and motor design factors. We shall now simplify the discussion somewhat by dropping the distinction between design variables referring to the fuel and oxidizer individually. The analysis will again be restricted to a fixed propellant combination injected at a specified mixture ratio and at the same injection temperature.

Following Crocco's notation (3), we shall use the symbols

$$n_d = \frac{L_H}{L_{Mo}} \; (\equiv n') \qquad [29]$$

$$n_v = \frac{v_H}{v_{Mo}} \qquad [30]$$

and

$$n_t = \frac{(t_r)_H}{(t_r)_{Mo}} = \frac{n_d}{n_v} \qquad [31]$$

for the length, velocity, and residence time scale factors, respectively.

1 Similarity Requirements for the Steady Aerothermochemistry

Crocco has derived two rules, one for fixed Mach number and one for an invariant Damköhler similarity group D_I.

From the definition given for M in Equation [4] it is apparent that, for a given propellant mixture and similar temperature history, M will be constant if

$$v_H = v_{M0} \qquad n_v = 1 \qquad \text{(Rule C.I)} \qquad [32]$$

Furthermore, for fixed Reynolds number

$$p_H L_H = p_{Mo} L_{Mo}$$

whence it follows that

$$p_{Mo}/p_H = L_H/L_{Mo} = n_d \qquad \text{(Rule C.I)} \qquad [33]$$

Equations [32, 33] identify the essential results of Crocco's Rule I for scaling with fixed M.

Next, Crocco assumes that the chemical conversion time varies inversely as the pressure raised to the mth power, i.e.

$$t_i \propto \frac{1}{p^m} \qquad [34]$$

Since combustion similarity can be maintained only if every residence time t_r changes proportionally with the chemical time t_i, it follows that

$$t_i \sim t_r$$

Therefore, in view of Equations [31, 34]

$$n_t = \frac{(t_r)_H}{(t_r)_{Mo}} = \left(\frac{p_{Mo}}{p_H}\right)^m = \frac{n_d}{n_v} \quad \ldots\ldots\ldots [35]$$

and, for constant Re

$$p_H v_H L_H = p_{Mo} v_{Mo} L_{Mo}$$

or

$$\left(\frac{p_{Mo}}{p_H}\right)^m = \left(\frac{v_H}{v_{Mo}}\frac{L_H}{L_{Mo}}\right)^m = (n_v n_d)^m \quad \ldots\ldots\ldots [36]$$

Comparison of Equations [35, 36] shows that

$$(n_v n_d)^m = n_d/n_v = n_t$$

or

$$n_v = n_d^{(1-m)/(1+m)} \qquad n_t = n_d^{2m/(1+m)} \qquad \text{(Rule C.II)} \ldots [37]$$

$$\frac{p_{Mo}}{p_H} = n_d^{2/(1+m)} \qquad \text{(Rule C.II)} \ldots\ldots\ldots [38]$$

Equations [37, 38] constitute the essential results of Crocco's Rule II. For $m = 1$, Equations [32], [37], as well as Equations [33], [38], become identical; thus we maintain both M and D_I invariant at the same time. On the other hand, for $m = \infty$, Equations [37, 38] reduce to the P-T relation.

Whether or not the assumption $m = 1$ (i.e., chemical conversion time inversely proportional to pressure) or $m = \infty$ (i.e., chemical conversion time independent of pressure) is a good approximation in any given case can only be determined experimentally. As has been emphasized in the discussion of the P-T rule, for diffusion-controlled processes the statement $m = 1$ is certainly inadmissible. On the other hand, ignition delay times in rocket engines often vary roughly inversely with the chamber pressure. For rocket chambers in which the transient ignition processes constitute the major portion of the chemical conversion time it is therefore apparent that $m = 1$ may constitute a fair approximation.

Crocco writes a composite expression for conservation of mass in the form

$$n = \frac{(pvd^2)_H}{(pvd^2)_{Mo}} \quad \text{(i.e., } n \text{ equals the ratio of flow rates in the rocket chamber)}$$

$$n = \frac{(pr^2)_H}{(pr^2)_{Mo}} \quad \text{(i.e., } n \text{ equals the ratio of flow rates through the nozzle throat)}$$

$$n = \frac{(v_i h^2)_H}{(v_i h^2)_{Mo}} \quad \text{(i.e., } n \text{ equals the ratio of flow rates in the injection orifices)}$$

$$n = \frac{(v_t A_t)_H}{(v_t A_t)_{Mo}} \quad \text{(i.e., } n \text{ equals the ratio of flow rates in the feed system)} \quad \ldots [39]$$

Using the relations given previously, it is now easily shown that

$$n = n_d \qquad \text{(all rules)} \ldots\ldots\ldots [40]$$

$$r_H/r_{Mo} = n_d \qquad \text{(Rule C.I)} \ldots\ldots\ldots [41]$$

$$r_H/r_{Mo} = n_d^{(1/2)+1/(1+m)} \qquad \text{(Rule C.II)} \ldots\ldots [42]$$

$$r_H/r_{Mo} = n_d^{1/2} \qquad \text{(P-T rule)} \ldots\ldots\ldots [43]$$

Furthermore, since $(v_i)_H/(v_i)_{Mo} = n_v$

$$h_H/h_{Mo} = n_d^{1/2} \qquad \text{(Rule C.I)} \ldots\ldots\ldots [44]$$

$$h_H/h_{Mo} = n_d^{m/(1+m)} \qquad \text{(Rule C.II)} \ldots\ldots\ldots [45]$$

$$h_H/h_{Mo} = n_d \qquad \text{(P-T rule)} \ldots\ldots\ldots [46]$$

Finally $$(v_t)_H/(v_t)_{Mo} = n_d(A_t)_{Mo}/(A_t)_H \ldots\ldots\ldots [47]$$

Comparison of Equations [41] and [42] and of Equations [44] and [45] shows that Crocco's Rules I and II again become identical for $m = 1$ and correspond to the case of no nozzle distortion, whereas the P-T rule (which is again obtained from C.II for $m = \infty$) always gives nozzle distortion. On the other hand, Equations [44–46] show that the orifice dimensions are scaled in proportion for the P-T rule but not for the Crocco rules. The practical significance of the indicated distortions cannot be assessed at the present time.

2 *Similarity of Cooling System*

Since the Reynolds and Prandtl numbers are fixed, the Nusselt heat transfer number also remains the same in the model and in the large engine. Hence the total heat which must be transferred to the motor walls, for chambers operating under similar conditions of temperature, pressure, and internal aerothermochemistry, must be directly proportional to the propellant consumption rate; this, in turn, varies linearly with the geometric scale factor, as has been shown in Equation [40]. Thus the total heat released and the total heat transfer to the motor walls must be directly proportional to $n = n_d$. Correspondingly the heat transfer per unit area varies as $n_d/n_d^2 = 1/n_d$.

Crocco has noted that complete similarity with respect to the cooling system will be maintained for constant coolant temperature and geometric wall scaling if the Nusselt number for the propellant(s) in the external flow also remains invariant, a condition which is easily achieved by maintaining geometric similarity for the coolant coils and constant Reynolds number in the coolant passages. The design of the cooling coils is closely related to the dynamic behavior of the feed system and must therefore be considered together with the problem of maintaining similarity for low-frequency stability (3).

3 *Similarity of Low-Frequency Stability*

Crocco (3) has discussed scaling procedures for a rigid and rigidly supported feeding system neglecting the compressibility of the propellants. Low-frequency stability depends on several parameters including the relative pressure drop $\Delta p/p$ (Δp = pressure drop across injection orifices; p = steady operating pressure in the combustion chamber) and an inertia parameter which equals the ratio of the kinetic energy of the propellants in the feeding system to the work done on the propellants by the pressure drops during the residence time. The inertia parameter can always be adjusted by suitable selection of the lengths and cross-sectional areas of the feed lines (3).

Since the pressure drop across the injector orifices is proportional to the square of the flow velocities v_i, we find that

$$\frac{\Delta p_H}{\Delta p_{Mo}} = \frac{(v_i^2)_H}{(v_i^2)_{Mo}} = n_v^2$$

whence

$$\epsilon \equiv \frac{(\Delta p/p)_H}{(\Delta p/p)_{Mo}} = \begin{cases} n_d & \text{for Rule C.I} \\ n_d^{2(2-m)/(1+m)} & \text{for Rule C.II} \\ = n_d^2 & \text{for the P-T rule} \ldots\ldots\ldots [48] \end{cases}$$

Thus the requirement $\epsilon = 1$ cannot be met in practice except for Rule C.II in the unlikely case that $m = 2$. For $m = 1$ the two rules of Crocco again become identical but lead to relatively low reduced injector drops in the model. Crocco has suggested the use of injector orifices with appropriately poorer flow characteristics in the model than in the large engine in order to compensate for this effect (3).

In the P-T procedure the pressure drop is too large in the model, thereby necessitating the use of relatively poorer injection orifices in the large engine than in the model in order to maintain $\epsilon = 1$. It is conceivable that this result can be obtained by physicochemical methods through appropriate

changes in interfacial tension and may, in fact, be consistent with the modifications which must be introduced in order to achieve relatively high injection velocities and small drop diameters in the model tests.

For some further details concerning the design of the feed system and of its relation to low-frequency instability problems we refer to Crocco's original manuscript (3). In this connection it appears appropriate to emphasize the fact that it is generally much easier in practice to eliminate undesirable low-frequency oscillations than the high-frequency oscillations.

4 High-Frequency Instability

As has been noted in Section IIC-2, high-frequency instabilities can presumably be controlled, for otherwise similar operating conditions, if the ratio of the chemical time t_i is fixed with respect to the wave propagation times t_w. But the latter are linear functions of the chamber dimensions for sound waves as well as for shock waves, provided the sound velocity remains invariant. Hence the similarity requirement for high-frequency instability may be written in the form

$$\frac{(t_i)_H}{(t_i)_{Mo}} = \frac{(t_w)_H}{(t_w)_{Mo}} = n_d \quad \ldots\ldots\ldots\ldots\ldots [49]$$

Using Equation [34] and the results for the pressure ratios given in Equations [33 and 38], respectively, it is readily shown that

$$\frac{(t_i)_H}{(t_i)_{Mo}} = \begin{cases} n_d{}^m & \text{for Rule C.I} \\ n_d{}^{2m/(1+m)} & \text{for Rule C.II} \end{cases} \quad \ldots\ldots [50]$$

The result for the P-T rule has been obtained in Equation [18]. The P-T rule corresponds again to the limiting relation obtained for Crocco's Rule II if m becomes very large.

Reference to Equations [49, 50] shows that the high-frequency stability of the system remains invariant as long as $m = 1$, irrespective of whether constancy of the Mach number M (Rule C.I) or of the first Damköhler similarity parameter D_I (Rule C.II) is enforced. The deficiencies of the P-T rule, in so far as the high-frequency stability requirement is concerned, have been noted previously in Section IIC-2.

Equation [49] expresses only the condition for similitude of the driving and coupling forces for oscillations. These forces producing oscillations must be balanced against the damping forces, of which the principal sources must be frictional losses. These, in turn, should be similar as long as the Reynolds number is constant. Damping associated with the oscillating gas flow through the nozzle is not similar unless the nozzles are scaled with maintenance of complete geometric similarity (which is always the case for Crocco's Rule I and applies also to Rule II if $m = 1$). However, for a well-designed prototype it appears unlikely that damping through nozzle oscillations plays a dominant role.

5 Some Critical Remarks Relating to Crocco's Scaling Rules

It is apparent from the preceding discussion that Crocco has succeeded in deriving a consistent set of scaling rules only for the special case in which $m = 1$. His proposed method requires model tests at elevated pressures, a procedure which raises formidable experimental problems. Furthermore, for a well-performing small rocket engine operating at elevated pressures, the effective L^* required for acceptable chamber operation is probably practically independent of pressure. Therefore, the effective chemical time t_i (which may be considered to be the sum of (a) an ignition time varying roughly inversely with the pressure and (b) a conversion time which is nearly independent of pressure) may well be nearly independent of pressure since, under steady operating conditions, the ignition time may be short compared to the conversion time. For these reasons we believe that it is unlikely that scaling with maintenance of similarity for all important operating characteristics is a practical possibility for real monopropellant or bipropellant liquid-fuel rocket engines. Nevertheless, Crocco's ingenious approach to the scaling problem deserves extensive experimental verification, because, at the very least, his work can be used as an intelligent guide in the interpretation of experimental findings.

III A Rational Experimental Program for the Study of Engine Scaling Procedures

The survey given in Section II of theoretical studies relating to engine scaling procedures contains numerous obvious suggestions for an intelligent experimental program. We shall therefore content ourselves here with a few summary statements concerning some of the more promising ideas.

A Experimental Studies on the Effect of Pressure on Operating Characteristics

If $t_i \sim 1/p$, Crocco's scheme is logically complete and suggests model tests on small engines operating at elevated pressures. The most economical procedure would appear to involve the design of models, using the scaling rules for $m = 1$, based on known large engine performance data both for satisfactory and for unsatisfactory motors.[6] We consider it more likely that this approach will prove successful for nonhypergolic bipropellant systems with components of roughly equal volatility (e.g., RFNA gasoline) than for either hypergolic mixtures or for propellants with greatly different volatilities.

B Experimental Studies on the Effect of Injection Velocity and Droplet Size on Motor Performance

The simplest way to answer the question concerning the importance of the steady aerothermochemistry would appear to be through the use of the P-T rule and the construction of small models, again on the basis of the known performance of large engines. In this connection, it is of primary importance to initiate studies on the control of spray distribution by physicochemical methods. As has been emphasized in the discussion given in Section IIC, the P-T rule is most likely to apply to systems in which the components have greatly different volatilities (e.g., JP4-LOX, RFNA-NH_3).

C Diagnostic Modeling

Since it appears likely that neither the Crocco rules nor the P-T rule offer a general answer to the scaling difficulties, the most fruitful method of approach is probably a more fundamental one than those suggested in Sections IIIA and IIIB. We must learn what are the really important similarity parameters and which dimensionless groups are of secondary importance. It is therefore necessary to perform tests in which (a) the driving force for high-frequency oscillations remains invariant both with and without constant Reynolds number, (b) only the damping (i.e., the steady aerothermochemistry and/or the Reynolds number) is unchanged, and (c) only the Mach number is constant, etc.

Correlated with an experimental program on diagnostic modeling should be a concerted effort to define the phenomenological meaning of chemical times in rocket engines and their dependence on design variables, such as temperature, pressure, injector construction, etc. This work should ultimately lead to a new set of rules which, unlike those considered in the present discussion, have a firm experimental foundation and unquestionable practical value.

(*Continued on page 168*)

[6] According to a recent personal communication, Crocco is currently planning some experimental studies of this type.

Similitude Considerations in Turbojet Engines

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The turbojet engine consists of a number of components, including the entrance duct, compressor, combustor, turbine, afterburner, and nozzle, as indicated in Fig. 1. The air inlet and diffuser comprise part of the aerodynamic propulsive system, and therefore might be regarded as an engine component. Between the several component parts are usually placed various ducts which often function either as diffusers (compressing the air) or nozzles (expanding the air). Principles of physical similarity in turbojets are used in connection with description of performance of the components, estimation of engine performance at new conditions, and comparisons of engines of different scale. To understand the application of dimensional similitude principles to turbojet engines, we must consider their application to the various component parts. We will begin with a discussion of physical similarity principles in flow and combustion systems, then consider briefly the application of these principles to the separate engine components, and finally make some observations concerning the engine as a whole.

1 Similitude in Flow and Combustion Systems

IF THE behavior of a physical system is described by a certain set of equations, and if the equations are put in dimensionless form by use of characteristic values of velocity, length, density, etc., coefficients will appear in them in the form of dimensionless groups. The values of these coefficients, along with the several boundary conditions, then determine the form of the solution. The solution will be in terms of dimensionless variables. Its counterpart in nature will be a family of geometrically and physically similar systems.

Even if the equations are not known in detail, if the independent variables are known, application of the principles and methods of dimensional analysis (1)[2] will permit the deduction of the dimensionless groups.

For viscous compressible gas flows, with constant specific heats and transport properties, the conditions for similitude have long been known (2), and they are that the following dimensionless groups should be alike in model and prototype (body forces neglected)

$$\left.\begin{array}{lll} \dfrac{u_c L \rho_c}{\mu} = Re_c & & \text{Reynolds number} \\ \dfrac{u_c}{\sqrt{kRT_c}} = M_c & & \text{Mach number} \\ \dfrac{\mu c_p}{\lambda} = P_r & & \text{Prandtl number} \\ \dfrac{c_p}{c_v} = k & & \text{specific heat ratio} \end{array}\right\} \quad \ldots\ldots [1]$$

The meaning of the symbols is

u_c	=	characteristic velocity
L	=	characteristic length
ρ_c	=	characteristic density
T_c	=	characteristic temperature
μ	=	viscosity
R	=	gas constant for gas used
c_p, c_v	=	specific heats
λ	=	thermal conductivity

When λ, μ, c_v, c_p depend on temperature, the characteristic values, λ_c, μ_c, c_{vc}, c_{pc} replace those in Equation [1]. Similitude requires the constancy of

$$Re_c = \frac{\mu_c L \rho_c}{\mu_c}, \; M_c = \frac{u_c}{\sqrt{k_c R T_c}}, \; Pr_c = \frac{\mu_c c_{pc}}{\lambda_c},$$

$$k_c = \frac{c_{pc}}{c_{vc}}, \; \frac{T_c}{T^\circ} = \tau_c \ldots [2]$$

and, in addition, the functions defining the temperature dependence of λ, μ, c_v must be alike[3]

$$c_v = c_v^\circ f_c(T/T^\circ), \quad \lambda = \lambda^\circ \cdot f_\lambda(T/T^\circ), \quad \mu = \mu^\circ \cdot f_\mu(T/T^\circ) \ldots [3]$$

Here, T° is a constant reference temperature. If the temperature dependence of k is very slight, and if f_λ and f_μ are power functions, then the requirement of constant τ_c in model and prototype may be relaxed. If different gases are used at the same temperature T_c, it is necessary that f_c, f_λ, f_μ be of the same form for each gas, even though c_v°, λ°, μ° may differ.

When combustion is taking place in the gaseous phase in a reaction chamber, into which streams of gaseous fuel and oxidant are injected, the conditions for similarity may be analyzed either by consideration of the detailed equations (3), or by an over-all view of the process using the methods of dimensional analysis. Following the latter course, we list the independent variables for a combustion system with specified fuel and oxidant gases[4]

F	=	fuel/oxidant ratio
u_c, ρ_c, T_c	=	characteristic speed, density, temperature
L	=	characteristic length
R_c	=	gas constant of oxidant
μ_c	=	characteristic viscosity
λ_c	=	characteristic thermal conductivity
D_c	=	characteristic diffusivity
c_{vc}	=	characteristic specific heat
Δh°	=	enthalpy of complete combustion at reference state
T°	=	reference temperature
w_c	=	characteristic rate of disappearance of a species (mass/sec per unit vol)
T_f	=	fuel temperature

Following usual dimensional analysis procedures, we deduce that the dimensionless parameters required in this case are

$$\left.\begin{array}{llll} F, & \dfrac{\Delta h^\circ}{R_c T_c}, & T_f/T^\circ = \tau_f, & \dfrac{R_c + c_{vc}}{c_{vc}} = k_c, \\ \dfrac{\mu_c}{\rho_c D_c} = Sc_c, & & T_c/T^\circ = \tau_c, & \dfrac{w_c L}{u_c \rho_c} = Z_c \\ \dfrac{u_c \rho_c L}{\mu_c} = Re_c, & \dfrac{u_c}{\sqrt{k_c R_c T_c}} = M_c, & \dfrac{\mu_c (R_c + c_{vc})}{\lambda_c} = Pr_c & \end{array}\right\} \quad \ldots [4]$$

Presented at the ARS Fall Meeting, Buffalo, N. Y., Sept. 24–26, 1956.

[1] Section Manager, Thermodynamics, Research Laboratories. Mem. ARS.

[2] Numbers in parentheses indicate References at end of paper.

[3] Temperature dependence of c_p and k is determined by that of c_v.

[4] Reference may be made to the work of Damköhler (4) who was one of the first to investigate similitude in combustion systems.

Note that we have fourteen variables and ten parameters, four less than the number of variables, as one would expect from the presence of four dimensions: length, time, mass, and temperature.

There are also, of course, a great many dependent dimensionless variables, one of considerable importance being the combustion efficiency η_B.

For similarity of two combustion systems we must have T_c constant, not only because of the effect of temperature variations on transport properties, but also because doubling inlet temperature will not by any means double the outlet temperature (since temperature rise is related to $\Delta h°$). Two burners with different inlet temperatures and the same fuel:air ratio could not behave similarly because the density ratio from outlet to inlet would not be the same for both. There are also other reasons, bound up with reaction kinetics, but the above argument suffices.

For fixed fuel and oxidant compositions in a family of geometrically similar combustors, the combustion efficiency would be expected to behave as follows

$$\eta_B = \varphi(F, Re_c, M_c, \tau_f, Z_c, \tau_c) \quad [5]$$

since k_c, Pr_c, and Sc_c are fixed, once oxidant composition and temperature are specified.

The quantity w_c, the characteristic species consumption rate, is a measure of the speed of reaction of the selected fuel and oxidant.

A possible definition of w_c could be formulated as follows: Let the fuel and oxidant used in the combustor under consideration be mixed in stoichiometric proportions at temperature T_c and pressure p_c, where p_c is $\rho_c R_c T_c$. Then let a laminar flame propagate through this mixture. The thickness of the reaction zone of this flame, according to some agreed upon definition, may be called δ_c. Then the rate of oxygen consumption in this zone, per unit of frontal area and per unit of δ_c, could be regarded as w_c. This is not to suggest that such experimental determinations need to be made to apply similitude principles to combustion. It is mentioned merely to illustrate the concept of a transformation rate characteristic of the fuel and oxidant, the temperature T_c and pressure p_c.

The characteristic transformation rate so defined will depend for fixed fuel and oxidant and fixed temperature level on density raised to a power n, which may be regarded as an effective over-all reaction order

$$w_c = C\rho_c^n \quad [6]$$

Actually, this is an approximation, for all the various reactions taking place in the laminar flame mentioned above will have their own reaction orders, $n_1, n_2, n_3, \ldots$; and, their combined effect is only represented by [6] as an empirical approximation. Similarly, in the combustion chamber, a change in pressure level would affect the rates of different reactions differently, and here it is assumed that the over-all effect may be fairly accurately represented by pressure raised to a power n.

A further remark concerning Equation [5] is in order. It is necessary to inquire if Re_c, M_c, τ_c, and Z_c can all be assigned arbitrarily. With T_c and M_c assigned, u_c is determined. If Re_c is assigned, then $\rho_c L$ is determined. But, with $C\rho_c^n$ in place of w_c, we have an assigned value of $\rho_c^{n-1}L/u_c$, and hence of $\rho_c^{n-1}L$, when u_c is determined. Simultaneous assignment of particular values to $\rho_c L$ and $\rho_c^{n-1}L$ will determine ρ_c and L. Hence, for fixed values of all the parameters in the right-hand member of Equation [5], only one combustor size and operating condition is possible, and there is no possiblity of similitude of combustors of different size. (An exception to this conclusion occurs when $n = 2$.)

One way out of this difficulty is to observe that for low Mach numbers, compressiblity is unimportant. We then have

$$\eta_B = \varphi_1(F, Re_c, \tau_f, \tau_c, Z_c) \quad [7]$$

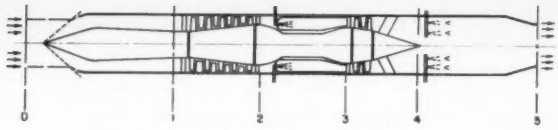

Fig. 1 Turbojet engine with afterburner

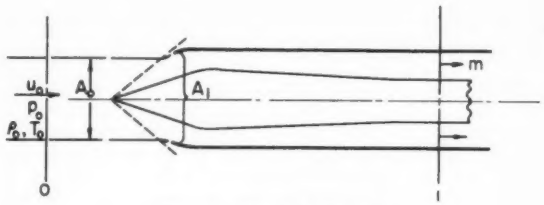

Fig. 2 Inlet and diffuser

2 Application to Engine Components

We consider first the inlet and diffuser section, represented in Fig. 2. The walls are assumed to be adiabatic. Characteristic flow speed and state quantities may be taken in the free stream, with subscript zero. It would appear at first that the quantities which must be alike for similitude of geometrically similar systems are (M_0, Re_0, Pr_0, k_0, τ_0), and also the functions f_c, f_λ, f_μ of Equation [3]. If air is used in both systems Pr_0 and k_0 drop out. However, there is a further important requirement for similitude, which pertains to the boundary conditions. It is that mass flow ratio m/m_0 be the same for the two systems, where m is mass flow rate in the inlet, m_0 is $\rho_0 u_0 A_i$, and A_i is intercepted area by the inlet lip. The mass flow ratio is influenced by the flow restriction downstream of station 1. If the flow restriction is (in whole or in part) near station 1, its form must be the same in the two systems to insure similar velocity profiles at station 1. In some instances where M_0 is supersonic and flow is supersonic just downstream of the diffuser throat, m/m_0 is determined solely by inlet geometry and flow parameters M_0, Re_0, etc. The downstream restriction then influences the shock location in the diffuser and determines the pressure ratio p_1/p_0. This latter ratio then takes the place of m/m_0 in the similarity considerations.

If air is the fluid and geometrically similar models are used, the quantities (M_0, Re_0, τ_0, m/m_0) must, therefore, be alike for similitude, with p_1/p_0 replacing m/m_0 under the conditions mentioned above.

Performance of the inlet and diffuser may be measured by total pressure ratio p_{1t}/p_{0t} or by a pressure recovery ratio $(p_1 - p_0)/(p_{0t} - p_0)$. The total pressure ratio and diffuser outlet Mach number will be functions of the four variables

$$\left.\begin{aligned} p_{1t}/p_{0t} &= f_1(M_0, Re_0, \tau_0, m/m_0) \\ M_1 &= f_2(M_0, Re_0, \tau_0, m/m_0) \end{aligned}\right\} \quad [8]$$

For moderate variations of T_0, τ_0 may be ignored.

Since we are now dealing with duct flows and will have, in general, nonuniform velocity, temperature, and pressure profiles, some conventions must be adopted in defining the mean value of flow quantities at any station. From measurements of local values in the stream of flow direction, T_t, p_t, and p, the local Mach number and values of T, u_x, ρ, h, and h_t can be deduced. If m is mass flow, H is stream convected enthalpy, H_t is convected total enthalpy and S convected entropy

$$m = \int_A \rho u_x dA, \quad H = \int_A \rho u_x h dA,$$

$$H_t = \int \rho u_x \left(h + \frac{u^2}{2}\right) dA, \qquad S = \int_A \rho u_x s dA$$

At station 1, for example, mean specific enthalpy and entropy values may then be defined as

$$h_1 = H_1/m, \qquad h_{1t} = H_{1t}/m, \qquad s_1 = S/m$$

Temperatures T_1 and T_{1t} which characterize the flow at station 1 may be taken as those corresponding to h_1 and h_{1t}, while pressures p_1 and p_{1t} could be considered as those corresponding to (T_1, s_1) and (T_{1t}, s_1). The density, velocity, and Mach number characteristic of the flow at the section could then be considered to be

$$\rho_1 = p_1/RT_1, \qquad u_1 = u_{1x} = m/\rho_1 A_1, \qquad M_1 = u_1/\sqrt{k_1 R T_1}$$

Simpler formulations, such as simply using average values over the section, would also suffice for similarity considerations. In any case, representation of the nonuniform distributions by single values is bound to be somewhat arbitrary.

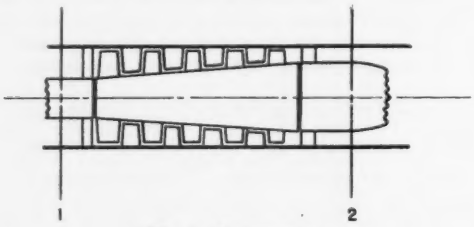

Fig. 3 Compressor

We turn attention next to the compressor, Fig. 3. Since we have now to deal with moving blades, the relative Mach number becomes important, as well as the Mach number of the flow relative to any stationary blade. Let r_c be the blade tip speed in the compressor. The flow field in the compressor depends on the geometry, inlet velocity, and temperature profiles, and on the factors

$$(M_1,\ Re_1,\ \tau_1,\ v_c/\sqrt{k_1 R T_1},\ k_1,\ Pr_1)$$

and on the functions f_c, f_λ, f_μ. For air as working fluid the group reduces to

$$(M_1,\ Re_1,\quad \tau_1,\ v_1/\sqrt{k_1 T R_1})$$

Among the performance factors are the total pressure ratio α_c, dimensionless enthalpy rise y_c, and efficiency η_c.

$$\alpha_c = \frac{p_{2t}}{p_{1t}}, \qquad y_c = \frac{2(h_{2t} - h_{1t})}{v_c^2}, \qquad \eta_c = \frac{h_{2t}' - h_{1t}}{h_{2t} - h_{1t}}$$

These parameters will depend on the several independent compressor variables. For geometrically similar compressors operating on air with similar inlet flow profiles they will be

$$\alpha_c = F_1(M_1,\ Re_1,\ \tau_1,\ v_c/\sqrt{k_1 R T_1}) \ldots\ldots\ldots\ldots [9]$$

$$y_c = F_2(M_1,\ Re_1,\ \tau_1,\ v_c/\sqrt{k_1 R T_1}) \ldots\ldots\ldots\ldots [10]$$

$$\eta_c = F_3(M_1,\ Re_1,\ \tau_1,\ v_c/\sqrt{k_1 R T_1}) \ldots\ldots\ldots\ldots [11]$$

Enthalpy h_{2t}' corresponds to total pressure p_{2t} and entropy s_1, as indicated in Fig. 4. For the afore-mentioned family of similar compressors, the outlet restrictions must be similar in so far as they influence the velocity profile at station 2.

The variables in the right-hand members of Equations [9, 10, 11] are those which must be alike for similitude of geometrically similar compressors running on air. The factor τ_1, which is $T_1/T°$, can be disregarded for moderate variations of T_1. It appears in the equations only on account of the temperature dependence of c_v, λ, and μ. The Reynolds number is of some influence when its variation is considerable, as occurs, for example, in going from sea level to high altitude (5, 6).

Formulations [9, 10, 11] are consistent with usual practice in describing compressor performance by means of "corrected" quantities. The corrected speed N', corrected air flow m', and

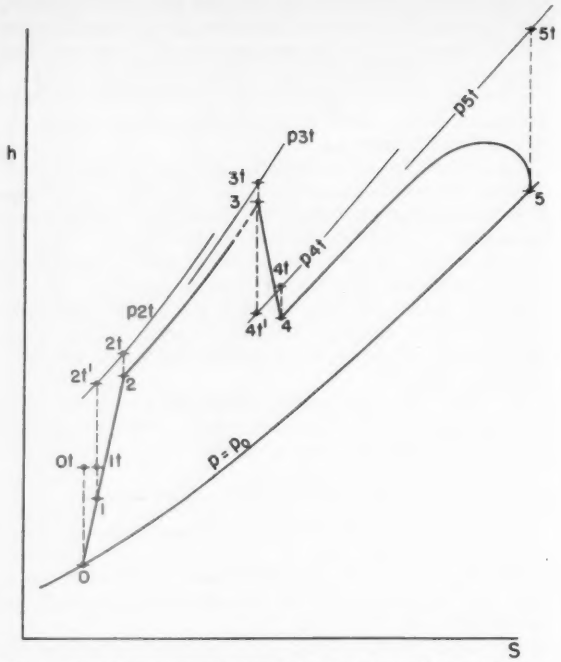

Fig. 4 Enthalpy-entropy diagram for turbojet with afterburner; case of $p_5 = p_0$

corrected compressor power Y_c, may be defined as

$$N' = N\sqrt{\frac{T_{SL}}{T_{1t}}}, \qquad m' = m\sqrt{\frac{T_{1t}}{T_{SL}}} \cdot \frac{p_{SL}}{p_{1t}}, \qquad Y_c = \frac{h_{2t} - h_{1t}}{N^2}$$

where N is actual rpm, and T_{SL}, p_{SL} are sea level standard atmospheric values. If a certain "design point" for the compressor is specified, and N', m', Y_c, α_c are expressed as fractions of design point values, one has the relations

$$\frac{\alpha_c}{\alpha_{c\ des}} = G_1\left(\frac{m'}{m'_{des}},\ \frac{N'}{N'_{des}},\ Re_1,\ \tau_1\right) \ldots\ldots [12]$$

$$\frac{Y_c}{Y_{c\ des}} = G_2\left(\frac{m'}{m'_{des}},\ \frac{N'}{N'_{des}},\ Re_1,\ \tau_1\right) \ldots\ldots [13]$$

$$\eta_c = G_3\left(\frac{m'}{m'_{des}},\ \frac{N'}{N'_{des}},\ Re_1,\ \tau_1\right) \ldots\ldots [14]$$

The fractional values are easily shown to be related to the parameters used previously, and Equations [12, 13, 14] may be used alternatively to [9, 10, 11] to describe compressor performance. The influence of τ_1 is, as before, quite small.

Following the compressor, the air enters the combustion section, Fig. 5. The diffuser at the combustor inlet and the transition section leading to the turbine are regarded as part of the combustor. Characteristic values of the flow variables are taken at station 2.

Though the fuel may be injected as a liquid, it quickly transforms to a gas. We will treat the combustor, for the present, as one with gaseous fuel injection. Assuming air is the oxi-

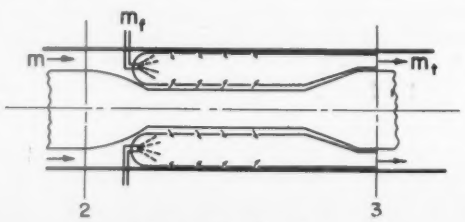

Fig. 5 Combustor

dant, and fuel type is fixed, we have seen in Section 1, Equation [5], that burning efficiency and other performance factors will depend on six parameters. The performance factors may, therefore be expressed as

$$\eta_B = \varphi_1(F, M_2, Re_2, \tau_f, \tau_{2t}, Z) \quad [15]$$

$$T_{3t}/T_{2t} = \varphi_2(F, M_2, Re_2, \tau_f, \tau_{2t}, Z) \quad [16]$$

$$p_{3t}/p_{2t} = \varphi_3(F, M_2, Re_2, \tau_f, \tau_{2t}, Z) \quad [17]$$

where $\tau_f = T_f/T^\circ$, $\tau_{2t} = T_{2t}/T^\circ$, and $Z = w_c L/\rho_2 u_2$. At low Mach numbers in the combustion chamber compressiblity effects are not important and M_2 may be ignored.

For two geometrically similar combustors, A and B, operating at low Mach numbers with the same fuel and oxidant (air), the same fuel:air ratio, the same inlet temperature conditions (τ_f and τ_{2t}), and similar processes of gaseous fuel injection, similitude of flow and combustion patterns will be expected if Re_2 and Z are alike for A and B, or

$$\left.\begin{aligned}(u_2\rho_2 L)_A &= (u_2\rho_2 L)_B \\ (\rho_2{}^{n-1}L/u_2)_A &= (\rho_2{}^{n-1}L/u_2)_B\end{aligned}\right\} \quad [18]$$

Note that constant C in Equation [6] depends on gas composition and temperatures, and, hence, will be alike for the similar combustors A and B. Under the afore-mentioned limitations, combustion efficiency depends on Re_2 and β, where $\beta = \rho_2{}^{n-1}L_2/u_2$, so that we have in place of Equation [15]

$$\eta_B = \varphi_1'(Re_2, \beta) \quad [19]$$

Alternatively to β one might also use the variable $m/V\ p_{2t}{}^n$, where V is flame tube volume.

The legitimacy of using relations [18, 19] depends upon the soundness of the assumptions that compressibility effects are trivial and that the effects of pressure change on the speeds of the various reactions may be adequately taken account of by the over-all reaction order n which leads to a variation of characteristic transformation velocity with ρ^n. It is implied also that n is constant over a considerable range of pressure. To evaluate the soundness of these assumptions, mention may be made of some experimental results.

The experiments of Longwell and Weiss (7) with stirred turbulent reactors showed that the blowout point, for fixed fuel, fuel:air ratio, and inlet temperature, depended on $m/V\ p_t{}^n$ for similar combustors of three sizes at various pressures. The value of n for iso-octane and solvent naphtha fuels was found to be 1.8. Here, influence of Reynolds number variation was negligible. Experiments carried out by Woodward (8) show dependence of η_B on Re_2 and β for constant fuel:air ratio and inlet temperature in geometrically similar combustors of three different sizes. It appears that the use of relations [18] or [19] is justified. Some of Woodward's results are shown in Fig. 6. An n value of 1.64 was indicated, with propane fuel.

It is of interest to note that similarity relations [18] imply equal values, for models A and B, of ratio of dimension L to flame quenching distance δ, and of flow speed u_2 to normal burning velocity S. Forming the product of the left and right members of Equations [18] one obtains

$$(L^2\rho_2{}^n)_A = (L^2\rho_2{}^n)_B$$

From the known dependence of quenching distance on pressure, for specified mixture and temperature conditions, it is to be expected that

$$(\delta\rho_2{}^{n/2})_A = (\delta\rho_2{}^{n/2})_B$$

and, therefore

$$(L/\delta)_A = (L/\delta)_B \quad [20]$$

Taking the quotient of the left and right members of Equations [18] gives

$$(u_2{}^2/\rho_2{}^{n-2})_A = (u_2{}^2/\rho_2{}^{n-2})_B$$

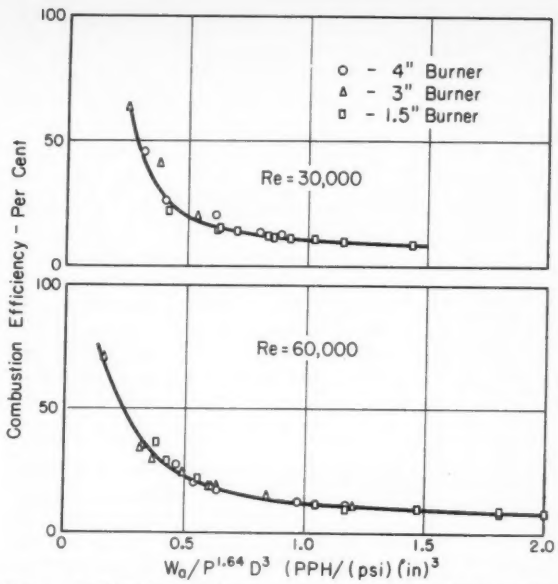

Fig. 6 Combustion efficiency vs. combustion intensity parameter

and from the known dependence of burning velocity on pressure with specified mixture and temperature

$$(S/\rho_2{}^{(n/2)-1})_A = (S/\rho_2{}^{(n/2)-1})_B$$

Therefore

$$(u_2/S)_A = (u_2/S)_B \quad [21]$$

It might, therefore, be considered reasonable to use condition [20] or [21] in place of the second of Equations [18]. It is felt, however, that the latter condition comes closer to taking account of the physical factors limiting the combustion process, as the quantity Z represents a ratio of residence time to reaction time.

Equations [18] may be solved for u_{2A}/u_{2B} and ρ_{2A}/ρ_{2B} in terms of L_A/L_B

$$\rho_{2A}/\rho_{2B} = (L_A/L_B)^{-2/n},\ u_{2A}/u_{2B} = (L_A/L_B)^{(2-n)/n} \quad [22]$$

For $n = 2$ density (or pressure) should vary inversely with size, while velocity should be held constant, for similitude. For $n = 1.6$ density varies as $L^{-1.25}$, while velocity varies as $L^{0.25}$.

When the fuel is injected as an atomized spray, we can make only an approximation to similarity in two models of different size. The injectors must be selected so that their inherent spray patterns (i.e., spray angles and mass distribution in the spray) are alike. Similar relations of fuel momentum to air momentum require that

$$\left(\frac{u_2}{w_0}\right)_A = \left(\frac{u_2}{w_0}\right)_B \quad [23]$$

where w_0 is velocity of droplets coming from the atomizer. We would like also to have droplets follow geometrically similar trajectories in the two combustor models. This means that if $\bar{w}$ is the local droplet velocity vector, then

$$\left(\frac{L}{w_0{}^2}\cdot\frac{d\bar{w}}{dt}\right)_A = \left(\frac{L}{w_0{}^2}\cdot\frac{d\bar{w}}{dt}\right)_B \quad [24]$$

From dynamical considerations, a good approximation of the acceleration is

$$\frac{d\bar{w}}{dt} = \frac{18\mu_g\bar{w}'}{d^2\rho_f}(1 + 0.2R_{ed}{}^{0.6}) \quad [25]$$

where μ_g, ρ_g are gas viscosity and density around the droplets, d is droplet diameter at some point of its trajectory, R_{ed} is $w'\rho_g d/\mu_g$, and $\bar{w}'$ is local gas velocity relative to the droplet.

Combination of [18, 23, 24, 25], with the consideration that $\bar{w}'/w_0$ and d/d_0 will be alike at corresponding points, and that the local Reynolds number R_{ed} may be replaced (for an approximation) by half the initial value, $^1/_2(w_0\rho_g d_0/\mu_g)$, leads to

$$\left\{\left(\frac{L}{d_0}\right)^2 \cdot \frac{\rho_2}{\rho_f}\left(1 + 0.2\left[\frac{w_0\rho_g d_0}{2\mu_g}\right]^{0.6}\right)\right\}_A = \left\{\left(\frac{L}{d_0}\right)^2 \cdot \frac{\rho_2}{\rho_f}\left(1 + 0.2\left[\frac{w_0\rho_g d_0}{2\mu_g}\right]^{0.6}\right)\right\}_B \quad \ldots [26]$$

Consideration of mass transfer processes shows that d/d_0 will indeed be essentially the same at corresponding points of droplet trajectories of the two models. Atomizers would have to be used giving w_0 and d_0 so as to satisfy Equations [23, 26]. These equations comprise a statement of the approximate conditions for similitarity, in addition to Equations [18], when fuel is injected by liquid atomizers. They represent some improvement over the suggested approximation in a previous paper of the author (9).

In applying combustion similitude principles in the complete engine, retention of constant Mach number M_2 becomes important. We have seen that similar burners of different size cannot operate with duplicate values of M_2, Z, and Re_2. Fortunately, the combustor behavior is not sensitive to small variations in Reynolds number, and they will indeed be small if M_2 and Z are constant. Consequently, a compromise is in order, and for applications to the engine, Equations [18] are replaced by

$$\left.\begin{aligned}(u_2/\sqrt{k_2RT_2})_A &= (u_2/\sqrt{k_2RT_2})_B \\ (\rho_2{}^{n-1}L/u_2)_A &= (\rho_2{}^{n-1}L/u_2)_B\end{aligned}\right\} \quad \ldots [27]$$

and the same restrictions as we had for [18] apply, except that M_2 need not be low.

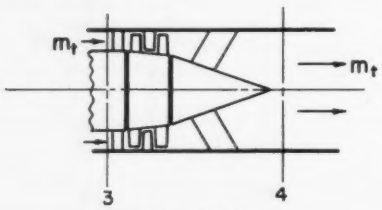

Fig. 7 Turbine

The next component part, in order, is the turbine. Fig. 7. With appropriately defined inlet and outlet flow parameters, as mentioned previously, the description of turbine performance in dimensionless form, and the corresponding expression of conditions for similarity, closely parallels that presented for the compressor.

Characteristic values are taken at the turbine inlet, station 3. Corresponding to Equations [9, 10, 11], we have, for a family of similar turbines running on a particular gas mixture

$$\left.\begin{aligned}\alpha_t &= F_4\left(M_3, Re_3, \tau_{3t}, \frac{v_t}{\sqrt{k_3R_3T_3}}\right) \\ y_t &= F_5\left(M_3, Re_3, \tau_{3t}, \frac{v_t}{\sqrt{k_3R_3T_3}}\right) \\ \eta_t &= F_6\left(M_3, Re_3, \tau_{3t}, \frac{v_t}{\sqrt{k_3R_3T_3}}\right)\end{aligned}\right\} \quad \ldots [28]$$

where $\tau_{3t} = T_{3t}/T^\circ$, v_t is turbine wheel tip speed and

$$\left.\begin{aligned}y_t &= \frac{h_{3t} - h_{4t}}{\frac{1}{2}v_t{}^2} \\ \eta_t &= \frac{h_{3t} - h_{4t}}{h_{3t} - h_{4t}'}\end{aligned}\right\} \quad \ldots [29]$$

Similar turbines, running on the same gas, will yield similar performance and present similar flow patterns when the parameters in the right-hand members of [28] are alike. Parameter τ_{3t} enters, as in the case of the compressor, to take proper account of temperature dependence of specific heats and transport properties.

In the more common technical formulation of turbine performance, we would have corresponding to Equations [28] (and to Equations [12, 13, 14] for the compressor)

$$\left.\begin{aligned}\frac{\alpha_t}{\alpha_{t\,des}} &= G_4\left(\frac{m_t'}{m_t'_{des}}, \frac{N_t'}{N_t'_{des}}, Re_3, \tau_{3t}\right) \\ \frac{Y_t}{Y_{t\,des}} &= G_5\left(\frac{m_t'}{m_t'_{des}}, \frac{N_t'}{N_t'_{des}}, Re_3, \tau_{3t}\right) \\ \eta_t &= G_6\left(\frac{m_t'}{m_t'_{des}}, \frac{N_t'}{N_t'_{des}}, Re_3, \tau_{3t}\right)\end{aligned}\right\} \quad \ldots [30]$$

where

$$N_t' = N_t\sqrt{\frac{T_{SL}}{T_{3t}}},\ Y_t = \frac{h_{3t} - h_{4t}}{N_t{}^2},\ m_t' = m_t\sqrt{\frac{T_{3t}}{T_{SL}}}\cdot\frac{p_{SL}}{p_{3t}} \quad \ldots [31]$$

The mass flow m_t is slightly different from m on account of the injected fuel. The relation, for fuel:air ratio F, is

$$m_t = (1 + F)m \quad \ldots [32]$$

Here, N_t is turbine rpm, in general the same as compressor rpm, N.

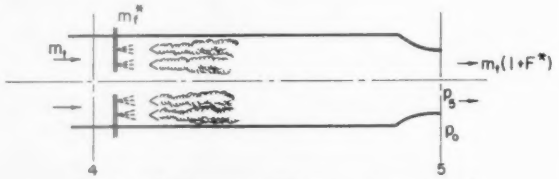

Fig. 8 Afterburner; either $p_5 = p_0$ or $M_5 = 1$

In the afterburner and exhaust nozzle system, Fig. 8 (taken together since some burning often occurs in the nozzle), we again have a combination of flow and combustion phenomena. Fuel at rate m_f^* is added to the vitiated mixture approaching station 4. Taking characteristic values at station 4, the afterburner performance is described by

$$\left.\begin{aligned}\eta_B{}^* &= \psi_1(F^*, Re_4, M_4, \tau_f{}^*, \tau_{4t}, Z^*) \\ \frac{T_{5t}}{T^\circ} &= \psi_2(F^*, Re_4, M_4, \tau_f{}^*, \tau_{4t}, Z^*) \\ \frac{p_{5t}}{p_{4t}} &= \psi_3(F^*, Re_4, M_4, \tau_f{}^*, \tau_{4t}, Z^*) \\ M_5 &= \psi_4(F^*, Re_4, M_4, \tau_f{}^*, \tau_{4t}, Z^*)\end{aligned}\right\} \quad \ldots [33]$$

for given gas composition at station 4 and specified fuel. Here, F^* is the ratio $m_f{}^*/m_t$ and Z^* is $w_c{}^*L/\rho_4 u_4$, while $w_c{}^*$ is a transformation velocity characteristic of the afterburner. Also, $\tau_f{}^*$ is $T_f{}^*/T^\circ$ and τ_{4t} is T_{4t}/T° and $T_f{}^*$ is afterburner fuel temperature.

For two afterburner models, geometrically similar, running on the same incoming gas composition and the same fuel, both at fuel:gas ratio F^*, and with the same fuel temperature and inlet temperature, similitude of performance will be realized when

$$\left.\begin{aligned}(u_4\rho_4L)_A &= (u_4\rho_4L)_B \\ (p_4{}^{n-1}L/u_4)_A &= (\rho_4{}^{n-1}L/u_4)_B \\ (u_4/\sqrt{k_4R_4T_4})_A &= (u_4/\sqrt{k_4R_4T_4})_B\end{aligned}\right\} \quad \ldots [34]$$

Since k_4, R_4, and T_4 are alike for models A and B, fulfillment of these conditions is only possible for second-order reactions, $n = 2$. For n different from 2, it probably would be ad-

visable to relax the Reynolds number requirement (first of Equations [34]) and maintain Mach number and reaction rate parameters (last two of Equations [34]). Mach number here is important not only because of its role in the adjacent engine components but also because compressibility phenomena occur in the afterburner.

In applying the similitude conditions [34] in the afterburner, it must be assumed that the fuel is injected in such a manner that similar fuel concentration patterns are obtained in the vicinity of the flameholders. Detailed discussion of this problem is beyond the scope of this paper. It would appear, however, that a minimum requirement should be similarity of the locations of the points of fuel injection, similar directions of injection, and similar velocities of injection (w_0/u_4 ratios).

3 The Engine as a Whole

The externally controllable variables in the operation of a turbojet engine are the free stream inlet air state quantities and Mach number, the fuel rate to the main burner, the fuel rate to the afterburner, and the outlet nozzle geometry.[5] When these variables are fixed, the engine will find its own operating point, at which turbine speed N_t equals compressor speed N, turbine flow equals compressor flow plus fuel flow, and turbine shaft power equals compressor shaft power plus the small power required to overcome bearing losses and drive auxiliaries. If inlet, compressor, combustor, turbine, and afterburner characteristics are known, the operating point can be predicted.

The relations for the independent and dependent dimensionless parameters for the complete engine take the form, for fixed geometry

$$\left.\begin{aligned}
\frac{v_c}{\sqrt{k_0RT_0}} &= g_1(M_0,\ Re_0,\ \tau_c,\ F,\ F^*,\ \tau_f,\ \tau_f{}^*,\ Z,\ Z^*)\\
T_{3t}/T_{0t} &= g_2(M_0,\ Re_0,\ \tau_c,\ F,\ F^*,\ \tau_f,\ \tau_f{}^*,\ Z,\ Z^*)\\
T_{5t}/T_{0t} &= g_3(M_0,\ Re_0,\ \tau_c,\ F,\ F^*,\ \tau_f,\ \tau_f{}^*,\ Z,\ Z^*)\\
p_{2t}/p_{0t} &= g_4(M_0,\ Re_0,\ \tau_c,\ F,\ F^*,\ \tau_f,\ \tau_f{}^*,\ Z,\ Z^*)\\
\frac{P}{p_{0t}A_i} &= g_5(M_0,\ Re_0,\ \tau_c,\ F,\ F^*,\ \tau_f,\ \tau_f{}^*,\ Z,\ Z^*)\\
f\sqrt{k_0RT_0} &= g_6(M_0,\ Re_0,\ \tau_c,\ F,\ F^*,\ \tau_f,\ \tau_f{}^*,\ Z,\ Z^*)
\end{aligned}\right\} \quad [35]$$

where P is engine thrust and f is specific fuel consumption, mass of fuel per second per unit of thrust.

The above relations could also be derived by combination of the Equations [8, 9, 17, 28, 33], etc., for the various components, together with the matching relation for compressor power and turbine power, and use of either the choking condition $M_5 = 1$ or $p_5 = p_0$ at the afterburner nozzle throat. (A convergent nozzle is here assumed.) Compressor and turbine rotative speeds are alike, which determines a relation of v_t to v_c. Since in most cases the afterburner fuel is the same as the main engine fuel, it suffices to take $Z^* = Z$. The fuel temperature parameters are, in general, of slight effect unless their variation is large. Hence, the group of engine independent variables becomes essentially

$$(M_0,\ Re_0,\ \tau_c,\ F,\ F^*,\ Z)$$

As has been mentioned in connection with discussion of the combustor, difficulties arise when one attempts to fix values of all these parameters for two geometrically similar engines of different size, unless reaction order n equals 2. A compromise must be made in establishing assigned values of Z, Re_0, and M_0. Since combustor performance is quite sensitive to variation in Z and since Reynolds number influence is generally quite small, it is considered that the best compromise is to allow Re_0 to change by the moderate amount that is necessary, while keeping the other variables fixed in two models in which we desire similitude. Velocities then remain constant in the two models at corresponding points, since Mach numbers and temperatures are constant. Constancy of M_0, τ_0, and Z, thus, would require that $\rho_0 L$ and Reynolds number vary as $\rho_0{}^{2-n}$. Hence, for two engine models at different densities

$$\frac{(Re_0)_A}{(Re_0)_B} = \frac{\rho_{0A}{}^{2-n}}{\rho_{0B}{}^{2-n}} \quad [36]$$

and we see that since n is not far different from 2, the differences in Reynolds numbers will be slight. For $n = 2$, Reynolds numbers would be alike.

When a successful engine has been built and it is desired to build a new engine of larger size, it might be considered expedient to enlarge dimensions of the main components by a constant geometrical factor. If the first engine gave certain performance at a certain altitude, 40,000 ft for example, at a certain flight Mach number and if the scale enlargement factor is 2, the second engine would be expected to give performance equivalent to that of the first, at a higher altitude at which the pressure is lower by a factor of $2^{1/(1-n)}$. With $n = 1.8$, the factor would be 0.42 and the new altitude, 58,220 ft. This is on a basis of duplicating Mach numbers and reaction rate parameters Z, rather than Reynolds numbers. The Reynolds number ratio would be $Re_B/Re_A = 0.84$, which is probably close enough to unity to be inconsequential.

As another example, we may note that when a large number of preliminary engine performance calculations are to be made it often is justifiable to neglect certain of the variables which are of secondary importance. In this instance, we note that Equations [35] may be revised so that T_{3t}/T_{0t} and T_{5t}/T_{0t} replace F and F^* as independent variables. The independent variable group becomes

$$(M_0,\ Re_0,\ \tau_c,\ T_{3t}/T_{0t},\ T_{5t}/T_{0t},\ \tau_f,\ \tau_f{}^*,\ Z,\ Z^*)$$

if we ignore τ_c, τ_f, $_t{}_f{}^*$, Z and Z^* in comparing two similar engine models, we shall be disregarding factors which influence combustion efficiency, and, hence, dimensionless specific fuel consumption $f\sqrt{k_0RT_0}$ might be different in the two otherwise similar models. If, however, it is known or assumed that for all contemplated operating conditions the combustion efficiency is high (say 95 per cent or better), then $f\sqrt{k_0RT_0}$ will be the same in the models being compared. The flow patterns, pressure and temperature ratios will be alike at corresponding points when the variables (M_0, Re_0, T_{3t}/T_{0t}, T_{5t}/T_{0t}) are alike. Going one step further in the approximation, if the influence of Re_0 is neglected, the approximate conditions for similitude would be that parameters in the following group remain constant

$$(M_0,\ T_{3t}/T_{0t},\ T_{5t}/T_{0t})$$

This makes possible short cuts in preliminary estimates of engine performance. For example, if analysis of a proposed design indicates the engine will have 10,000-lb thrust at $M_0 = 0.8$ at sea level with $T_{3t} = 2000$ R and $T_{5t} = 3400$ R, one can estimate performance at altitude at $M_0 = 0.8$. Thus, since $p_0 = 14.7$ psia, $T_0 = 518.7$ R, $p_{0t} = 22.4$ psia, $T_{0t} = 585$ R, and at 25,000 ft, for example, T_0 is 429.5 R and p_0 is 5.452 psia, the engine running at a temperature T_{3t} equal to 1658 R and T_{5t} equal to 2820 R at $M_0 = 0.8$ at 25,000 ft would devlop a thrust of 3700 lb. The rotor rpm would be lower than that at sea level by a factor of $\sqrt{429.5/518.7}$, or 0.91.

The use of such an approximation is justified when high accuracy is not a requirement and when a very large number of performance estimates and comparisons must be made.

Finally, a word may be added about "two-spool" turbojets. The speed factor for the second, or high pressure rotor, $v_c'/\sqrt{k_0RT_0}$, merely becomes another independent variable in the set of Equations [35] in this instance.

[5] Also, and of considerably less importance, fuel temperature.

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A Generalized Closed Form For Burnt Velocity

(*Continued from page 155*)

These data indicate that the drag (at burnout) can be a relatively large proportion of the thrust without appreciably affecting the required mass ratio. In the specific cases, as can be seen from Table 1 and 2, the drag would reach roughly one-third of the thrust before the drag-free calculation of mass ratios would be appreciably in error. This conclusion is unfortunately not true in general.

Because the drag appears in Fig. 3 in a rather involved fashion affecting both the scale and the parameter $1/R = 1/P, 1/Q$, this figure is inadequate for interpreting the effects of drag on the mass ratio velocity relationship. To illustrate the effect of drag, the simple case of a subsonic rocket is considered as follows: Equation [21a] is plotted in Fig. 4 for several representative values of $Q/2 = \delta\sqrt{K_{do}}$. This plot can also be used for [22a] as is indicated on the figure. Also shown are several dotted lines of constant drag-to-thrust at burnout, that is, $D_b/T = K_{do}\,\delta^2 v_b^2$. The curve marked $D_b/T = 0$ is coincident with the $\delta\sqrt{K_{do}} = 0$ curve and is the zero drag solution, Equation [1]. Plotting Equation [21a] in this manner relegates all of the dependence of drag to the parameter $\delta\sqrt{K_{do}}$. Noting this figure, it can be seen that the mass ratio is little affected by drag until a near-threshold value of drag-to-thrust is reached; then the effects become severe. For example, if $\delta\sqrt{K_{do}} = 6$, and $v_b/v' = 0.119$ ($D_b/T \cong 0.5$), the drag-free m_b/m_o is only 3.3 per cent too high. If, however, $v_b/v' = 0.159$ ($D_b/T = 0.9$), then the drag-free computation gives a result 11 per cent in error. It is impossible, using this same value of $\delta\sqrt{K_{do}}$ (thrust value and drag coefficient), to reach velocities greater than $v_b/v' = 0.166$.

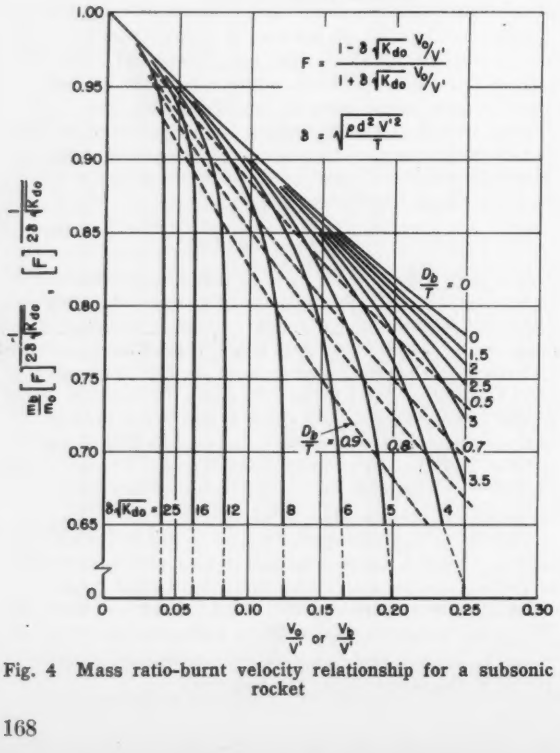

Fig. 4 Mass ratio-burnt velocity relationship for a subsonic rocket

Concluding Comments

In the foregoing it has been shown how the effects of drag may be included in design considerations. Methods of including drag in the computations have been developed such that the additional effort required is not prohibitive. As might be expected, drag is not a significant factor in the design of low-performance rockets.

The decision as to when drag must be included in design calculations is not a priori an easy one. In the drag-free analysis, there is no apparent limit to the burnt velocity attainable; thus to obtain increasing burnt velocity, one must only increase the launching velocity or decrease the inert mass. In reality, however, the velocity is limited by the condition "drag equals thrust" and near this limit drag-free calculations are seriously in error.

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Rational Scaling Procedures for Liquid-Fuel Rocket Engines

(*Continued from page 161*)

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Effect of Turbulence on Radiation Intensity From Propane-Air Flames

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As a continuation of a general investigation of the characteristics of high speed turbulent flames, the effect of turbulence on flame radiation intensity was measured in order to determine the extent of the possible interaction between the mixing process and the chemical reaction. It was thought that such interaction could reveal itself by an observable change in the energy radiated per unit mass of fuel. The energy measurements were made with a standardized photomultiplier through three interference filters centered, respectively, at 4500 Å for CO background radiation, 5150 Å for C_2, and 4300 Å for CH. In each case, turbulence reduced the specific intensity of the radiation. The reductions were greatest (up to 35 per cent) for fuel-lean mixtures for the highest intensities of turbulence, and were stronger for CO than for either CH or C_2. These results indicate that the turbulent mixing does break up what would be a continuous laminar flame sheet, and that this breakup modifies the chemical reaction and transport processes in the flame zone. This conclusion is in agreement with the hypothesis advanced in a previous paper, that the turbulent flame is not merely a distorted laminar flame but rather a deep zone of chemical reaction. In this paper, the magnitude of the intensity reduction is interpreted in terms of the ratio of the "chemical time" to the "mixing time," and it is concluded that flames of the type studied here are in the range of unity for this parameter.

Introduction

THE study of high intensity turbulent combustion is of importance, practically, in connection with modern high output combustion systems and, scientifically, as an example of a close interaction between aerodynamics and chemical kinetics. Qualitatively, it is well known that the presence of turbulence in the stream entering into a combustion zone tends to shorten the combustion zone and thus increase the over-all space heating rate. However, at present, after more than a decade of research on turbulent flames, it is not possible to predict with any degree of certainty the specific effect of a prescribed scale and intensity of turbulence on either (a) the external characteristics, e.g., flame speed or space heating rate, or on (b) the internal chemical and physical structure of a turbulent combustion zone. The present investigation, which is part of a study on turbulent flame structure initiated at Princeton University in 1953, is designed to cast some light on these questions.

The various physical models proposed as an explanation for the behavior and structure of a turbulent flame zone can be divided into two classes: Either the turbulent flame zone is a zone of wrinkled or broken up "laminar flames" (Damkohler, 1940; Karlovitz, 1951) or it is a relatively deep reaction wave characterized by turbulent energy transport and turbulent mixing of reactants and products (Schelkin, 1943; von Kármán, 1953; Summerfield, 1954). Experiments carried out in this laboratory, and reported previously (5),[3] led to results which could not be reconciled with the model of a turbulent flame zone based on the existence of laminar flamelets. Instead, the results indicated that the turbulent flame is really a zone of reaction distributed in depth.

This conclusion was based on four types of experiments:

1 Filtered photographs of an open turbulent flame brush through a 4300 Å filter (CH emission) and through a 9300 Å filter (H_2O emission) showed that the onset of H_2O emission lagged behind the onset of the CH emission at distances of from 2 to 10 mm in various parts of the flame zone. This is in contrast to the spatial lag of less than $^1/_2$ mm for the laminar hydrocarbon air flame zone at atmospheric pressure.

2 Comparison of the position of the contour of maximum luminosity (4300 Å) with thermocouple traverses through an open turbulent flame brush indicated that the position of 85 per cent temperature rise and maximum luminosity was coincident. If the flame zone consisted of a fluctuating laminar flame or laminar flamelets, the position of maximum luminosity would correspond to the point of 50 per cent temperature rise.

3 Measurements of the conductivity fluctuations in an open turbulent flame brush showed that there was always an appreciable ion concentration in contact with some portion of the ion probe.

4 Finally, short duration (20 microsec) spark shadowgraphs gave no evidence of either a wrinkled laminar flame or laminar flamelets in the open turbulent flame zone.

These experiments have recently been corroborated, in part, by the work of Grumer (6) at the Bureau of Mines. Grumer reported horizontal conductivity traverses through a premixed stoichiometric (natural gas-air) open turbulent flame brush at Reynolds numbers of 25,000, 50,000, and 100,000 ($1^1/_4$-in. tube). It was again determined that the high levels of ionization in the flame brush were completely random and presented no indication of the "on-off" signal which would be characteristic of a wandering laminar flame.

Having reasonably established that a fully developed turbulent flame brush is a zone of extended or distributed reaction, the question next arises as to the mechanism of propagation and internal structure of this type of flame zone. A critical question, in this regard, is that of determining whether the changes in the volumetric heating rate and flame structure, observed with variation in the turbulent flow conditions, are a purely hydrodynamic process or connected with changes in basic chemical rates and mechanism.

It has been suggested by a number of workers (7, 8, 9) that the visible radiation emitted by a hydrocarbon flame can be considered as characteristic of the chemical processes occurring in the flame front. Typical emission spectra for fuel-rich and fuel-lean premixed propane-air flames are presented in Fig. 1. For fuel-rich flames the most prominent feature of the spectrum is the system of bands due to the excited C_2 radical (10)

Presented at the ARS Annual Meeting, New York, N. Y., Nov. 26–29, 1956.

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[3] Numbers in parentheses indicate References at end of paper.

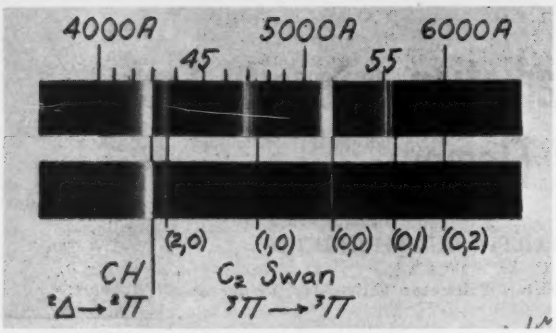

Fig. 1 Emission spectra for fuel rich (top) and fuel lean (bottom) laminar propane-air flames at atmospheric pressure

with band heads at 4700, 5150, and 5600 Å (Swan system). At 4300 Å, there is a band due to the excited CH radical (11) which is prominent in both fuel-rich and -lean flames. Finally, for long photographic exposures, it is also possible to observe a continuous spectrum, due to the bimolecular combination of CO and O (12), which covers the range from 3000 to 6000 Å. This association as a source of radiation is identified hereafter with the symbol CO_2^*.

These radicals appear to play a minor role in the combustion reactions since they are present in very small concentrations in laminar flame zones (13). However, the radiations and the concentrations of these radicals, propitiously, are sensitive functions of fuel type, air-fuel ratio, mixture temperature, and pressure. Therefore, they can serve as tracers for the more important chemical processes occurring in the flame.

The first systematic comparisons of the visible radiation from laminar and turbulent flames were made in 1954 by Gaydon and Wolfhard (8) in Great Britain and by Clark and Bittker (9) of the NACA.

Gaydon and Wolfhard carried out an exploratory series of measurements comparing the radiation intensity from laminar and turbulent Bunsen burner flames under conditions of "natural" and induced turbulence. Measurements were made photographically with a small quartz spectrograph. Comparisons of the flame spectra, at identical mixture strengths, but at Reynolds numbers above and below transition, and with and without a turbulence grid in the incoming flow, indicated that there were no qualitative changes in the appearance of the spectra or in the relative strengths of the C_2 and CH bands in the blue and green regions of the spectrum. They reported a 20 per cent decrease in intensity due to turbulence, but the experimental scatter was large.

The experiments of Clark and Bittker were quite similar to those of Gaydon and Wolfhard in that they were carried out on Bunsen burner flames under approximately the same conditions of fuel flow (4 to 20 cc/sec) and tube Reynolds number (1000 to 6000). However, in this case the radiation was measured using a photomultiplier tube and two spectrally broad dye filters rather than with a spectroscope and photographic plate. Comparisons were made of the photomultiplier response to the visible radiation emitted by the combustion of identical volumes of fuel subject to different flow conditions. Typical results are indicated in Fig. 2. Unlike the findings of Gaydon and Wolfhard, there was no observable change in the quantity of radiation per unit volume of fuel (at identical fuel equivalence ratios) as a result of turbulence.

The conclusions of Gaydon and Wolfhard and of Clark and Bittker were severely limited by the low levels of turbulence involved. The experimental program to be described was planned to check their initial work and to extend it in the following directions: (a) Higher levels of turbulence energy were produced by means of grids and confinement of the flame in a duct. (b) Narrower spectral isolation of the significant radiations was achieved by using narrow band interference

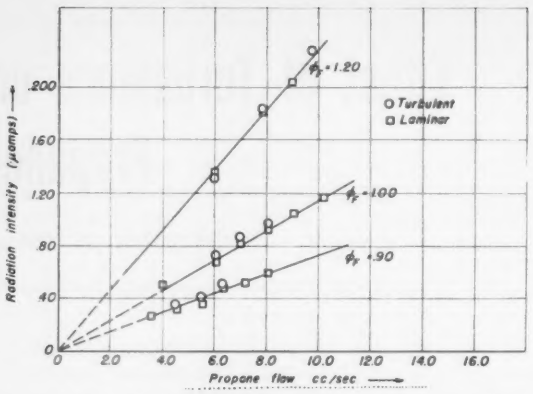

Fig. 2 Variation with fuel flow of laminar and turbulent flame intensities measured through yellow filter (reproduced from Reference 9)

filters. (c) Radiation measurements were made on an absolute basis which eliminated the requirement for an arbitrary geometrical relation between the source and receiver.

Experimental Apparatus

Basically, the major objective of the present experimental program was to compare quantitatively the spectral radiant flux emitted by laminar and turbulent flame zones. The spectral radiant flux was detected with an RCA 931-A photomultiplier, and selected with three narrow band pass (100 Å) interference filters centered at 4300, 4500, and 5150 Å. The measurements are expressed in terms of the specific emittance $K_{F,\lambda}$, which is the apparent radiant energy flux/unit mass rate of fuel flow entering the flame zone[4]

$$K_{F,\lambda} = \frac{W_{F,\lambda}}{Q_F} = \frac{i_{F,\lambda} C_{pm\lambda} 4\pi r_F^2}{Q_F} \ \mu \text{ watt/cc/sec/100 Å} \ldots [1]$$

$W_{F,\lambda}$ = total spectral emittance of the flame zone (μ watt/100 Å)
Q_F = propane flow entering flame zone (cc/sec, STP)
$i_{F,\lambda}$ = response of the combination photomultiplier-filter to the radiant flux emitted by all the volume elements in the flame zone (μ amp)
$C_{pm\lambda}$ = calibration of the photomultiplier and filter (μ watt/cm²/100 Å/μ amp)
r_F = mean distance from light sensitive area of photocathode to center of flame zone (cm)

In order to evaluate the emittance of the flame in absolute units of energy flux, the photo-receiver system was calibrated by use of a standard carbon filament lamp supplied by the National Bureau of Standards. A clear tungsten lamp was used as a secondary standard for higher ranges of energy flux after calibration with the carbon standard.

The calibration of the radiation receiver is given by the equation

$$C_{pm\lambda} = \frac{J_{L,\lambda}}{i_{L,\lambda}} \ \mu \text{ watt/cm}^2\text{/100 Å/}\mu \text{ amp} \ldots\ldots [2]$$

$J_{L,\lambda}$ = spectral radiant flux from the standard light source incident on the radiation receiver (μ watt/cm²/100 Å)
$i_{L,\lambda}$ = response of the photomultiplier tube and filter to the spectral radiant flux emitted by the standard radiation source (μ amp)

[4] For experimental convenience, the apparent energy flux is calculated from the photomultiplier signal on the assumption that the flame emits a continuous spectrum of uniform intensity within the transmission interval of the filter. In actual fact, the flame spectrum is not uniform. The true energy radiated depends on the band shape and is taken into account in the factor γ in Equation [3].

Implicit in these definitions are the following conditions which were carefully checked experimentally: (a) the receiver calibration is independent of the angle of incidence of the rays entering the receiver assembly; this condition was assured by limiting the closeness of the broad flame to the receiver. (b) The receiver calibration is independent of the absolute value of the incident flux. (c) The flame zone behaves as a point source; this condition permits spherical integration to obtain the total emitted radiation. (d) The flame zone is nonself-absorbing. (The test for this condition is explained more fully later.)

Other important precautions regarding the radiation measurements were the careful control of the geometry of the optical arrangement and the elimination of both reflected and stray radiation. The latter was accomplished by surrounding the entire apparatus with a blackened, nonreflecting enclosure.

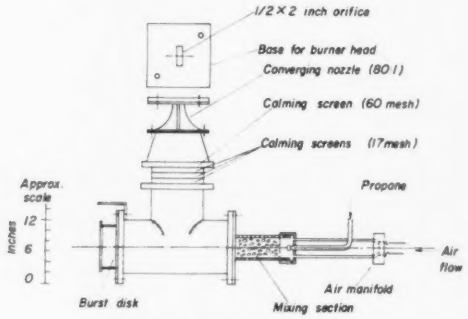

Fig. 3 Burner subassembly

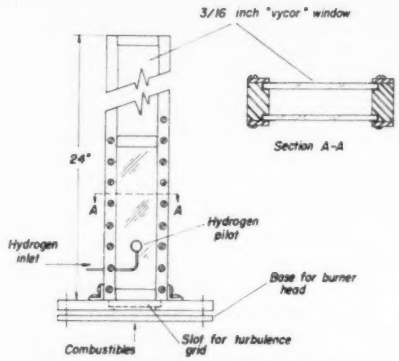

Fig. 4 Burner duct for enclosed flame

The drawings of the burners ($2 \times 1/2$ in. port) for the production of the open and enclosed piloted turbulent flame zones are shown in Figs. 3 and 4. A picture of the enclosed burner is presented in Fig. 5. The flow system was capable of supplying to this burner a steady flow of combustibles, with only occasional monitoring, for one hour or more of operation, at velocities up to 150 fps. The burner head for the production of the open flame zone consisted of a $1/2 \times 2$ in. central slot with two auxiliary slots for hydrogen flow to anchor the main flame. The enclosed burner consisted of a $1/2 \times 2 \times 24$ in. Vycor glass duct. In order to produce a stable flame in the duct it was necessary to use a small cylindrical rod flameholder with hydrogen pilot gas. The effect of the added hydrogen on the radiation was found to be negligible. Interchangeable turbulence grids could be mounted in the incoming flow directly below the open and enclosed burner heads. There were two conditions of inlet turbulence: One corresponded to burner operation without any grid (smooth discharge from the converging nozzle), and the other was turbulent flow produced by a 1/4-in. mesh grid (1/8-in. rods on 1/4-in.

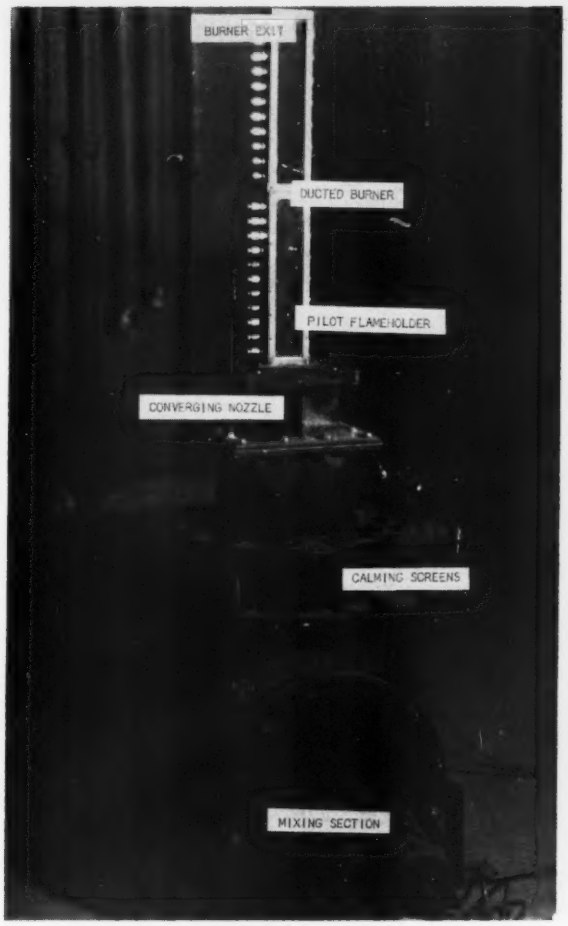

Fig. 5 Complete burner assembly

centers). In the latter case the turbulence intensity produced in the inlet flow was of the order of 10 per cent (14).

The fuel selected for the experiments was a commercial grade liquid propane (95 per cent propane, 5 per cent other hydrocarbons). To avoid possible errors in the measurements due to variations in the propane composition, all laminar-turbulent comparisons were made on a single tank of propane.[5] Further, in order to avoid possible separation of the heavy and light fractions of the impurity hydrocarbons, the propane was drawn, as liquid, from the bottom of the supply tank. Premixing of the propane and air was accomplished in a packed bed mixing section upstream of the flow calming screens (Fig. 3). Flow rates of air, propane, and hydrogen pilot flow were measured respectively by a rotameter and two orifice meters.

Laminar Propane-Air Flame

A knowledge of the characteristics of the visible radiation emitted by a laminar hydrocarbon-air flame is a prerequisite for any interpretation of the effect of turbulence on such radiation. The opening phase of the present program was then directed toward a quantitative study of the visible radiation emitted by a laminar premixed propane-air flame.

The shapes of the spectral bands for a fuel-rich and fuel-lean propane-air flame at atmospheric pressure are shown in Fig. 6. A calibrated RCA-931-A photomultiplier was used as

[5] Each tank of propane was treated separately, that is, the laminar-turbulent comparisons for the open and enclosed flames were made using two different tanks of propane.

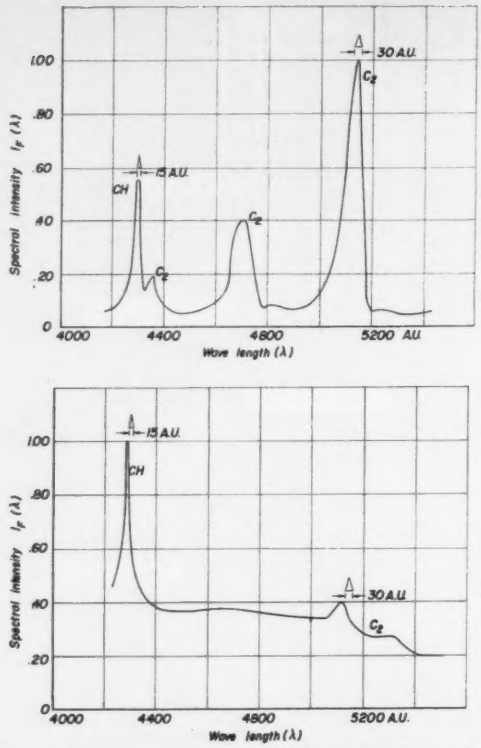

Fig. 6 Spectral intensity $I_{F,\lambda}$ vs. wavelength λ for a propane-air laminar flame sheet—equivalence ratio ϕF equal to 1.37 (top) and 0.78 (bottom)

the detector, and a small Hilger glass spectroscope, with fixed entrance and exit slits, as the selector.

Measurements of $K_{F,\lambda}$ for a nonabsorbing laminar propane-air flame sheet, which behaved as a point source, are presented in Fig. 8. If it is assumed that the residence time of the burning gas within the luminous zone (order of 10^{-4} sec) is long compared to the radiative lifetimes of the excited radicals (order of 10^{-8} sec), then the average rate of production of the emitting radicals is given by

$$\frac{dC_i}{dt} = \frac{\gamma(\phi_F,\lambda)K_{F,\lambda}S_L}{d_L(E' - E'')} \times \frac{1}{1 + a/f} \quad [3]$$

dC_i/dt = average rate of production of emitting radicals (mole/cc/sec)
$\gamma(\phi_F,\lambda)$ = effective spectral width of the emission band measured in multiples of 100 Å (see footnote 4)
S_L = laminar flame speed (cm/sec)
d_L = luminous thickness of laminar flame front (cm)
$(E' - E'')$ = energy involved in molecular transition (g-cal/g-mole)
$K_{F,\lambda}$ = spectral energy/unit mass of propane entering flame front (g-cal/cc/100 Å)
a/f = air-fuel ratio (volumetric)

Substituting values of $K_{F,\lambda}$ from Fig. 7, the calculated spectral widths for different spectral band shapes, and values of flame thickness and flame speed based on the works of Avery (15) and Singer (16), we obtain the curves of dC_i/dt vs. fuel equivalence ratio presented in Fig. 8. As an example it is noted that the maximum rate of formation of excited radiation-producing CH is of the order of 5×10^{-10} mole/cc/sec. From the measurements of flame speed and thickness for a propane-air flame at atmospheric pressure, the effective volumetric rate of consumption of propane is of the order of 5×10^{-3} mole/cc/sec. Thus, the volumetric rate of consumption of propane in a laminar flame front is approximately 10^7 times the rate of production of the emitters.

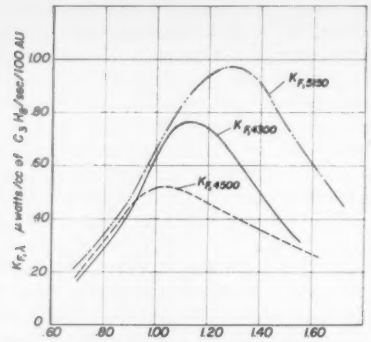

Fig. 7 Variation of specific emittance $K_{F,\lambda}$ with fuel equivalence ratio ϕF for a propane-air laminar flame sheet

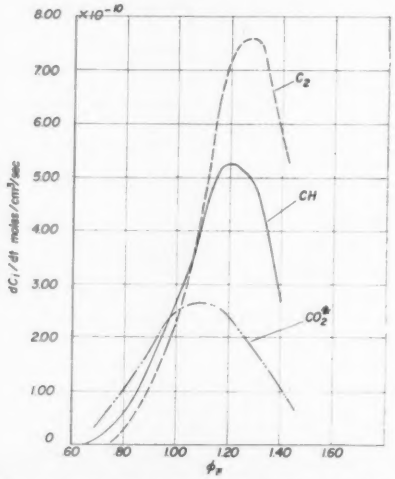

Fig. 8 Rate of formation of emitters dC_i/dt vs. fuel equivalence ratio ϕF for a propane-air laminar flame sheet

Assuming a quasi-steady rate of production, the average concentration of the emitting radicals in the flame zone is given by

$$C_i = \frac{dC_i}{dt}\tau \quad [4]$$

C_i = concentration of the emitting radicals in the flame zone (mole/cc)
τ = radiative lifetime (sec)

An order of magnitude value of the radiative lifetime is obtainable from quantum mechanical theory (17), i.e., approximately 10^{-8} sec. The computed values of the radical concentration are presented in Fig. 9.

In the final interpretation of the data, it is necessary to check for possible self-absorption of the C_2, CH, and CO_2* visible radiation by the radiating gases. If there were appreciable absorption, "thick" reaction zones would tend to indicate lower values of $K_{F,\lambda}$ than "thin" reaction zones. Due to uncertainties in the existing experimental (18) and theoretical estimates (19) of the self-absorption of visible radiation in thicknesses of flame greater than a laminar flame front, a series of experiments was carried out to determine the absorptivity of a "thick" (5 cm) reaction zone. Measurements were made of $K_{F,\lambda}$ for nearly laminar propane-air flame sheets on the open piloted burner, with the optical paths from the reaction zone first parallel and then perpendicular to the flame

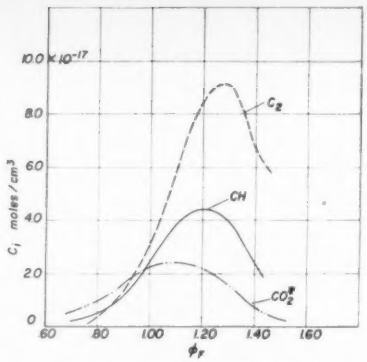

Fig. 9 Concentration of emitters C_i vs. fuel equivalence ratio ϕF

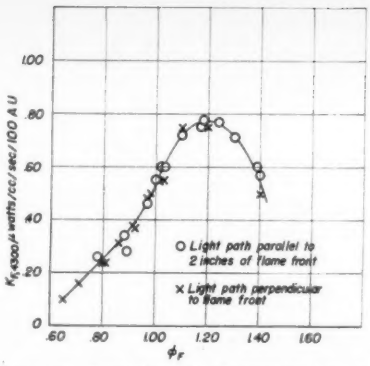

Fig. 10 Test for self-absorption for a propane-air laminar flame sheet

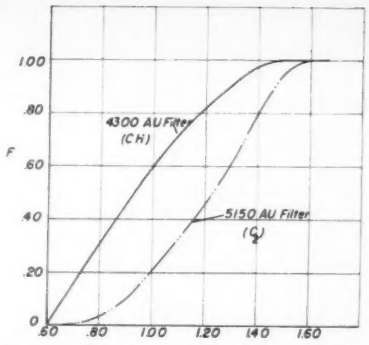

Fig. 11 Fraction of the photomultiplier response due to the CH and C_2 emitters

front. In this way it was possible to compare the radiation from "thick" and "thin" reaction zones, respectively. Results for the radiation transmitted by the 4300 Å filter in the two directions are presented in Fig. 10. Similar results were observed for the radiant flux transmitted by the 4500 and 5150 Å filters. Therefore, over the range of fuel equivalence ratios from 0.70 to 1.40, any absorption of the C_2, CH, and CO_2* radiation by thickness of flame up to 5 cm was too small to be detected.

Finally, estimates were made of the fraction of the radiant flux transmitted by the 4300, 5150, and 4500 Å filters due, respectively, to the CH, C_2, and CO_2* emitters. The fraction of the radiant flux transmitted by the interference filter and due to a particular emitter is given by

$$F = \frac{\int_0^\infty I_F(\lambda)_i P(\lambda) T(\lambda) d\lambda}{\int_0^\infty I_F(\lambda) P(\lambda) T(\lambda) d(\lambda)} \quad \ldots\ldots\ldots\ldots [5]$$

$I_F(\lambda)$ = relative spectral energy distribution from flame due to all emitters

$I_F(\lambda)_i$ = relative spectral energy distribution due to particular emitter in the flame

$P(\lambda)$ = relative spectral sensitivity of photomultiplier

$T(\lambda)$ = filter transmission factor

Plots of F vs. fuel equivalence ratio for the spectral bands of the excited CH and C_2 radicals at 4300 and 5150 Å are presented in Fig. 11. The 4300 filter transmits radiation from CH and CO_2*; the 5150 filter transmits radiation from C_2 and CO_2*. In the case of the radiation transmitted by the 4500 filter, the entire response is due to CO_2*.

Turbulent Flame—Open Burner

It is likely that a strong interaction between the aerodynamics and chemistry of combustion would affect the rate and/or the mechanism of production of each of the emitting species. The variation with flow conditions of the three $K_{F,\lambda}$, at fixed fuel equivalence ratio, may therefore be considered as indicative of the occurrence of such interaction. The experiments on the turbulent flame brush then consisted of the measurement and comparison of values of $K_{F,4300}$, $K_{F,4500}$, and $K_{F,5150}$, with similar quantities for a laminar flame zone. Photographs of typical turbulent open flame zones are shown in Fig. 12.

In Fig. 13 plots are presented of the reference curves of $K_{F,\lambda}$ vs. fuel equivalence ratio obtained on nearly laminar flame sheets at mean flow velocities of 28 and 42 fps.[6] Values of $K_{F,\lambda}$ were obtained for different open turbulent flame brushes, with a 4-mesh turbulence grid in the incoming flow, at mean flow velocities of 28, 42, 60, 85, 118, and 155 fps, and over a range of fuel equivalence ratios from 0.60 to 1.60. At the highest flow velocities the range of fuel equivalence ratios was narrowed, since the height of the flame became so large that it no longer behaved as a point source. Graphs of the specific emittance $K_{F,\lambda}$ vs. fuel flow Q_F at fixed fuel equivalence ratio ϕ_F are presented in Fig. 14. To avoid the uncertainties connected with the external burning of excess fuel in fuel-rich open flames, we have considered data only for fuel-lean equivalence ratios.

Taking the reduction in $K_{F,\lambda}$ as a measure of the effect of turbulence, the effect can be seen to be greatest for lean mixtures and for high rates of flow. The spectral bands at 4500 Å suffered the greatest percentage decrease, while the bands at 4300 Å decreased the least from the values of $K_{F,\lambda,\text{std}}$. Reference to the preceding section and Fig. 11 indicates that the spectral bands transmitted by the 4500 Å filter are due only to the CO_2* emitter, while the bands transmitted at 4300

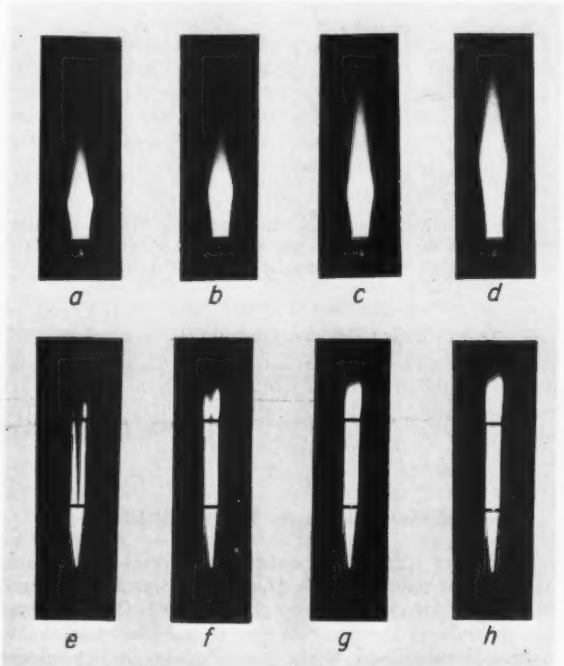

Fig. 12 Open and enclosed turbulent propane-air flames at an equivalence ratio equal to 0.90. Open: (a) 50 fps, (b) 100 fps, (c) 150 fps, (d) 200 fps. Enclosed: (e) 50 fps, (f) 100 fps, (g) 150 fps, (h) 200 fps

[6] The reference curves served as a consistency check on the propane composition, flow metering, and radiation detection systems, in that the specific emittances were obtained on different days and with different orifice meters.

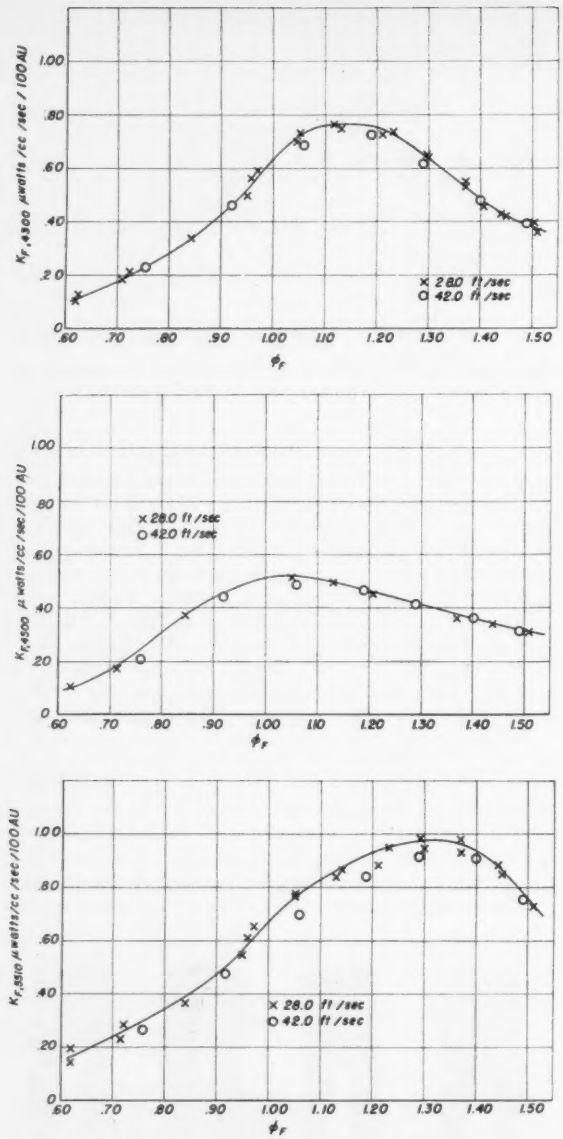

Fig. 13 Variation of spectral emittance $K_{F,\lambda}$ with fuel equivalence ratio ϕ_F for a laminar propane-air flame sheet; λ = 4300 Å (top), λ = 4500 Å (middle), λ = 5150 Å (bottom)

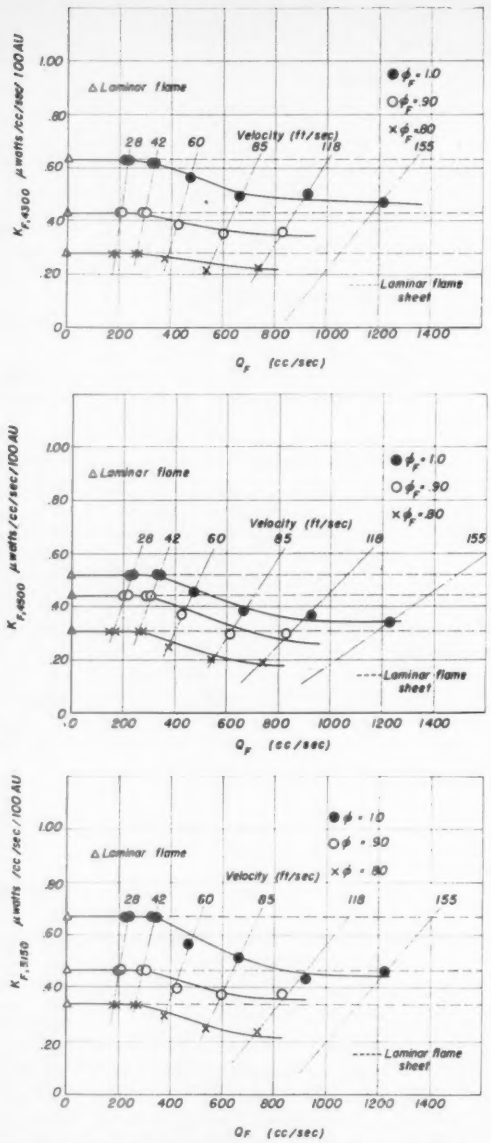

Fig. 14 Variation of spectral emittance $K_{F,\lambda}$ with fuel flow Q_F for an open turbulent flame brush; λ = 4300 Å (top), λ = 4500 Å (middle), λ = 5150 Å (bottom)

Å are due to both CO_2* and CH. It is suggested that the stronger effect at 4500 Å compared to the effect at 4300 Å indicates that the CO_2* emitter is affected by the aerodynamics of combustion to a greater degree than the CH radical. The implications of these results are discussed in greater detail below.

Turbulent Flame—Enclosed Burner

The burner with the enclosed duct was operated with a grid at mean flow velocities of 28, 42, 60, 85, 118, and 155 fps, and at fuel equivalence ratios from 0.70 to 0.90. Operation was not possible on the fuel-rich side of stoichiometric due to dynamic instabilities in the burner. Photographs of a series of typical enclosed turbulent flame zones are presented in Fig. 12.

The specific emittance $K_{F,\lambda}$ as a function of fuel flow and at fixed values of the fuel equivalence ratio has been plotted in Fig. 15.[7] Again, the effect of turbulence on $K_{F,\lambda}$ was greatest at the highest rates of fuel flow. As found in the open flame tests the bands at 4500 and 5150 Å suffered a greater decrease than the bands at 4300 Å, but the differences were not so pronounced. A tentative explanation for the less pronounced differences might be as follows: The values of the specific emittance for the enclosed flame were obtained in a leaner range of fuel equivalence ratios (0.70–0.90) than the values for the open flame (0.80–1.00). Therefore, since CO_2* becomes the dominant emitter in such lean flames, the three filters respond mainly to CO_2*, and only slightly to CH and C_2.

In making the measurements, it was assumed that absorp-

[7] It may be noted that the values of $K_{F,\lambda,std}$ for the enclosed flame series are below the values for the open flame series. The difference may be due to a difference in composition of the two tanks of commercial propane used in the open and enclosed flame measurements, respectively. No systematic effort was made to investigate this effect.

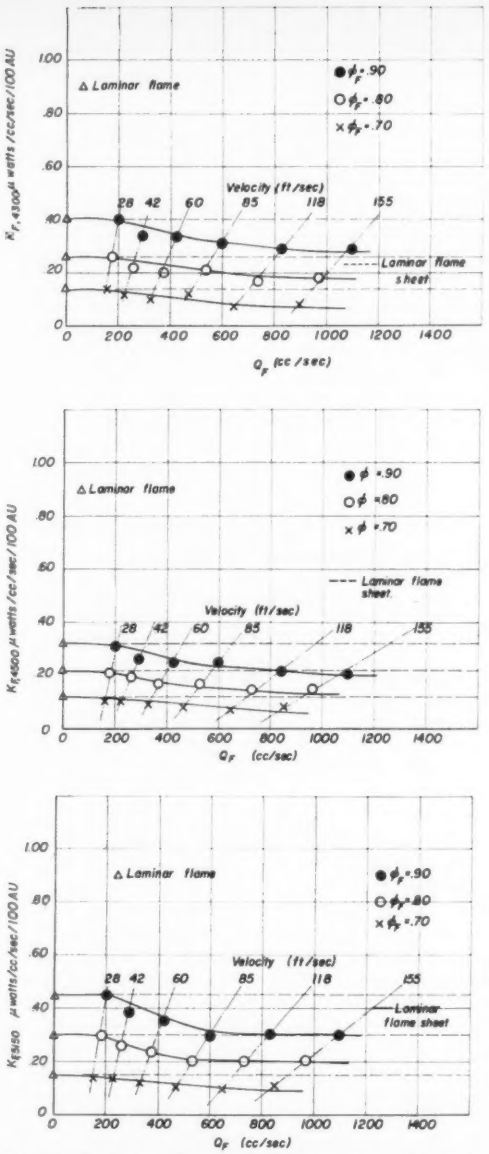

Fig. 15 Variation of spectral emittance $K_{F,\lambda}$ with fuel flow Q_F for an enclosed turbulent flame; λ = 4300 Å (top), λ = 4500 Å (middle), λ = 5150 Å (bottom)

tion of radiation by the Vycor window facing the radiation receiver was balanced by the reflection from the back Vycor window. No change was found in the reflectivity or the transmissivity of the Vycor in "hot" or "cold" flow.

A point of interest is that the radiation characteristics, i.e., values of $K_{F,\lambda}$ at constant ϕ_F, showed no observable change when the upstream grid was removed; this indicates that the turbulence in the flame zone was produced mainly by the strong shear flow in the duct during burning, and not by the grid.

Conclusion: Interpretation of the Turbulent Combustion Process

In general, the presence of turbulence in both the open and enclosed flame zones tended to reduce the values of $K_{F,\lambda}$. The observed reductions were largest with lean equivalence ratios and high flow velocities, and were more apparent for the flux transmitted by the 4500 and 5150 Å filters than the 4300 filter.

This effect of turbulence on specific radiation emittance can be best interpreted by comparison with other influences on flame radiation. It has been shown experimentally that changes in fuel equivalence ratio (Fig. 13) and mixture temperature (20) can cause as much as a tenfold change in the radiant flux emitted by a laminar flame zone. Since mixture ratio changes and preheating may be expected to occur locally in a zone of a turbulent flow, it is difficult to understand why the observed reduction due to turbulence is comparatively small (i.e., less than 35 per cent). In other words, the problem arises of forming a model for a zone of distributed reaction which brings into coincidence the earlier experimental determination that the reaction zone is not merely a distorted laminar flame (5) and the present experimental result that the chemistry of the reaction zone does not appear to be greatly affected by turbulence.

The small sensitivity of radical radiation to turbulence can mean only that, in the combustion of each element of fuel, the radical formation process is sufficiently rapid with respect to local environmental changes that it follows the same chemical path as in a normal laminar flame. This means that the time for the chemical step (τ_{chem}) must be shorter than the time for a small eddy to lose its identity (τ_{mix}). (The ratio of these times, i.e., τ_{chem}/τ_{mix} can be considered as a generalization of the parameter ($K = u'd_L/\lambda S_L$) proposed by Kovasznay (21) as a basis for separating the flow regime of the wrinkled laminar flame from that of the extended reaction zone. Large values of K would lead to breakup of the flame front. Low values of K would lead to a continuous wrinkled laminar flame.)

We therefore form the hypothesis that turbulence affects the combustion wave in the following way: Weak turbulence ($\tau_{mix} \gg \tau_{chem}$) merely wrinkles the laminar flame, producing an apparent thickening of the flame zone. Stronger turbulence ($\tau_{mix} \approx \tau_{chem}$) disrupts the continuous laminar flame front and spreads out the over-all reaction process. Still stronger turbulence ($\tau_{mix} \ll \tau_{chem}$) ultimately shows its effects by locally diluting and preheating the initial deflagration centers. Very intense flames of the last type were not observed in this research because of the limitations of the turbulence intensity that could be produced. The so-called homogeneous stirred reactor of Longwell (26) would be a case of $\tau_{mix} \ll \tau_{chem}$, and it would be of great interest to determine the radiation intensity for that burner.

In terms of this postulate, increased values of the mass flow of combustibles entering the flame zone, and decreased values of the fuel equivalence ratio, correspond, respectively, to a reduction in the value of τ_{mix}, and an increase in the value of τ_{chem}. Therefore, the observed reductions in $K_{F,\lambda}$ for high mass flow and lean fuel equivalence ratios are as expected. Similarly, since CO_2* is directly associated with the combustion of CO, which appears to be the slowest step in hydrocarbon combustion (22), the more pronounced effect of turbulence on the CO_2* emitter is not surprising.

Examination of the progressive decrease of $K_{F,\lambda}$ with increasing flow rate (Figs. 14 and 15) reveals a region of transition at about 30 to 40 fps. This transition probably corresponds to the range of $\tau_{mix} \approx \tau_{chem}$. Further study of the transition zone is desirable.

The previously observed (5) internal turbulent flame structure might also be explained in terms of the characteristic aerodynamic and chemical times. In the case in which τ_{mix} is approximately equal to τ_{chem}, it is proposed that the thickened flame front consists of a statistical distribution of deflagration centers which are reacting homogeneously, at any instant of time or point in space. During the time τ_{chem} the reacting center moves an average distance x, equal to the product of τ_{chem} and the mean local flow velocity U. Therefore, if one

(*Continued on page 178*)

Technical Notes

Comments on 'Thermonuclear Power Plants'

I. SHECHTMAN[1] and E. LARISCH[2]

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IN the July issue of JET PROPULSION (vol. 26, 1956,pp. 559–564) a paper by Hsue-shen Tsien, "Thermonuclear Power Plants," appeared. A paper by us on a similar subject ("On the Possibility of Applying Thermonuclear Reactions to Rocket Propulsion") appeared in *Studii si Cercetări de Fizică* (Studies and Researches in Physics), no. 2, 1956. As our paper arrives at conclusions quite contrary to those of Dr. Tsien, we would like to draw attention to certain statements and methods of calculation used by Dr. Tsien, which, in our opinion, are not correct and lead to these differences:

1 The most important parameter of the motor is its diameter. Dr. Tsien calculates it by evaluating the reaction "quenching zone" on the basis of similitude considerations. The value he finds is of the order of tens of meters. He justifies this method by affirming that it is not possible to use methods from astrophysics at such temperatures and densities, the mean free-path being of the same order of magnitude as the dimensions of the system. Affirming this, Dr. Tsien nevertheless applies Maxwell's distribution function to the calculation of the reaction rate, this being obviously in contradiction to the affirmation mentioned above.

A rigorous calculation, based on the physical properties of matter, leads to values many orders of magnitude greater. Even under a pressure of 10^4 atm (Dr. Tsien works with a pressure of only 100 atm) and a temperature of 10^6 K, the temperature gradient near the center is only $\sim 10^{-12} \cdot r$ K/cm, r being the distance from the center.

This result shows also that Dr. Tsien's afore-mentioned claim, that the mean free path is of the same order of magnitude as the dimensions of the system, is not valid.

2 Dr. Tsien chose for the reaction in the central zone a temperature of 1.6×10^8 K and a pressure of 100 atm. Under the condition of a thermodynamic equilibrium, this temperature and pressure cannot exist together, the radiation pressure alone amounting to 1.68×10^{12} atm.

Even if this is not taken into account, a temperature of 1.6×10^8 K is not the best choice.

As was shown in our paper, at a pressure of 100 atm the maximum rate of the tritium-deuterium reaction (Dr. Tsien works with the deuterium-deuterium reaction, which, in the absence of resonance, is slower and less energetic than the first) takes place at a much lower temperature, namely, at about 400,000 K and has the value of 10^{-15} cal/cm^3 sec, while Dr. Tsien finds the value of 0.87 cal/cm^3 sec. To get the Tsien figure, a pressure of approximately 50,000 atm is needed, the temperature at which the reaction rate is optimal being then 1.85×10^6 K. These differences are due to the fact that Dr. Tsien does not take into consideration the radiation pressure.

It was shown in our paper that the temperature gradient being extremely small, the temperature in the central zone should be chosen on considerations of maximum temperature gradient and not maximum reaction rate. For a pressure of 100 atm the temperature gradient has its maximum around 10^6 K and is extremely small. Even for a pressure of 10^4 atm it is only $\sim 10^{-11} \cdot r$ K/cm.

Finally, we want to draw attention to the fact that, as has been shown by G. Gamow and E. Teller,[3] in case a resonance exists in the domain of energies considered, the reaction rate is much greater.

A practical calculation, made in our paper and based on the above authors' work, shows that if the deuterium-deuterium reaction had a resonance at 1–2 KeV, its maximum rate might increase, for a pressure of 100 atm, by 10^5 times.

We would like to point out that some of our remarks—without detailed calculation, however—appear also in the note by Jesse L. Greenstein published in the same issue of JET PROPULSION in which the Tsien paper appears.

Received Dec. 12, 1956.

[1] Institute of Atomic Physics.

[2] Institute of Applied Mechanics.

[3] *Physical Review*, vol. 53, no. 7, 1938, p. 608.

The Earth-Mars Constant Thrust Brachistochrone

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A BRIEF investigation has been made of the constant thrust brachistochrone (path for minimum time) for interplanetary flights. In particular, the earth-Mars transfer orbit was studied for constant accelerations along the thrust vector of 10 to 1000 milligees (one milligee equals 0.0322 fps^2).

Constant accelerations within this range should eventually be feasible using nuclear propulsion systems. This range is of particular interest because of the short times which result for interplanetary flights. Higher accelerations are of less interest due to passenger discomfort. Lower accelerations or impulse thrusts are also of less interest because of the long times required for the one-way trip and the probable requirement for long waits on Mars for a second perihelion opposition.

For accelerations within the 10 to 1000 milligee range, variations in the sun's gravity field can be ignored. Acceleration due to the sun's gravity at the distance of the earth's orbit is approximately 0.6 milligees and at the orbit of Mars approximately 0.3 milligees. This represents only a 3 per cent variation for a net space ship acceleration of 10 milligees. Consequently, to simplify our study, the net acceleration was considered constant.

Assuming a highly efficient nuclear-fusion propulsion system, the mass of the ship can be considered constant. The mass of deuterium (in pounds) theoretically required to accelerate one ton of space ship is shown in Fig. 1 as a function of the total time for the inter-orbital transfer. Only orbital transfer time has been considered, and the gravity fields of the planets have been ignored. It is assumed that the ship is turned through 180 deg at the midpoint of the trip to reduce the radial velocity to zero at the orbit of Mars.

For the range of accelerations considered, the angular distance traversed is small compared to the planetary orbit and, for a first approximation, the orbits can be considered straight lines. (This is very similar to the "flat earth" approximation for short range projectiles.) The resulting brachistochrone is a symmetrical S-shaped parabolic curve tangent to the two

Received Dec. 15, 1956.

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EDITOR'S NOTE: This section of JET PROPULSION is open to short manuscripts describing new developments or offering comments on papers previously published. Such manuscripts are published without editorial review, usually within two months of the date of receipt. Requirements as to style are the same as for regular contributions (see masthead page of this issue).

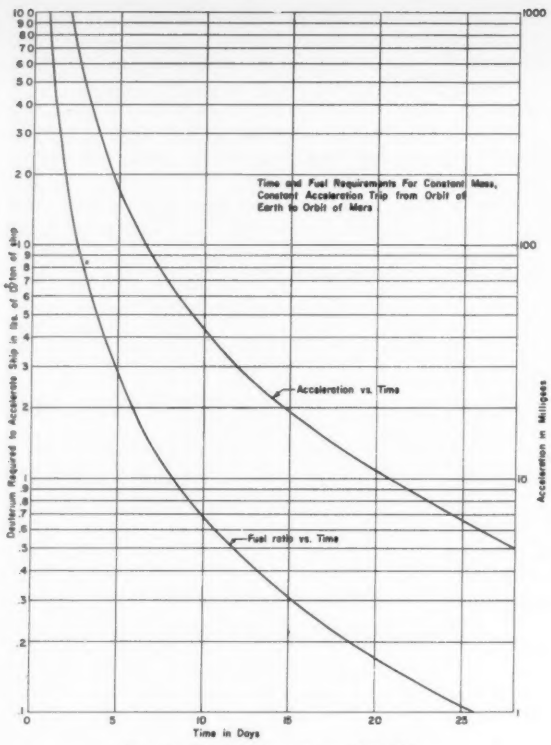
Time and Fuel Requirements For Constant Mass, Constant Acceleration Trip from Orbit of Earth to Orbit of Mars
Acceleration vs. Time
Fuel ratio vs. Time
Deuterium Required to Accelerate Ship in lbs. of ship
Acceleration in Milligees
Time in Days

Fig. 1 Earth-Mars interorbit trip

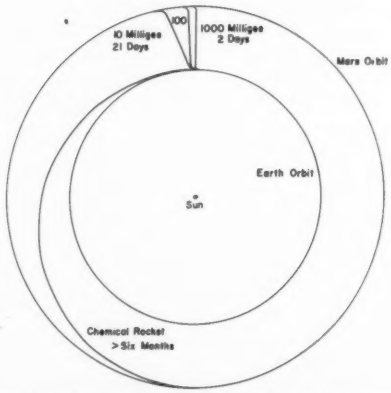

Fig. 2 Brachistochrones for constant thrust rockets compared to impulse thrust chemical rocket

planetary orbits and asymptotic to the orbit radius. The times required for the inter-orbit transfer are shown in Fig. 1 as functions of net acceleration. For 10 milligees the total time is approximately 21 days, and for 1000 milligees approximately 2 days.

It should be clear that, for the "flat orbit" approximation, time will be a minimum when the thrust vector does not change its orientation in inertial space (except for the midpoint turnaround) and is constantly perpendicular to the straight-line orbits.

Considerable work has been done by Lawden (1)[2] and others on the problem of transfer between planetary orbits with minimum expenditure of fuel. If chemical rockets are ever used for interplanetary flights, fuel conservation (through optimum application of thrust) will be essential. However, the excessive travel times involved make this method so unattractive that the "Mars Project" might be postponed indefinitely.

Once the almost unlimited energy in the nucleus of the atom is made available for space flight, emphasis will be shifted to transfer orbits that minimize time, rather than energy. Studies of fusion power plants, such as those by Tsien (2), Project Matterhorn, and others, along with studies of the application of nuclear energy to rocket propulsion, (3,4), have progressed to the point where it appears probable that nuclear, rather than chemical, energy will be used for long interplanetary flights.

Brachistochrones, for some constant net acceleration flights, are compared with a typical chemical rocket orbit in Fig. 2. The planetary orbits are approximated by circles. Trips will require from two days to three weeks for the range of accelerations considered. Performance of this order can be achieved with nuclear fuels with resulting enormous improvements over chemical rockets.

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Comparison of Reverse Jet and Obstacle-Type Flameholders

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TWO competitive methods of flameholding are at present under investigation at various laboratories throughout the country; one is the obstacle method which is also used in practical applications, and the other is the more recently suggested reverse jet method. Now that some information is available in the literature on the latter method (1, 2)[2] it is of interest to compare the two methods to see if they have any features in common.

To do this, the blockage-type flameholder is considered first. For high R_e, V_{bo}/F varies with D/δ, where V_{bo} is the blowoff velocity, F is the laminar burning velocity, D is the flameholder diameter, and δ is the laminar flame thickness (3). Since the drag force equals

$$C_D \left(\frac{\rho V^2}{2}\right)\left(\frac{\pi D^2}{4}\right)$$

the minimum obstacle diameter, D, necessary to hold a flame at V_{bo}, can be replaced by a constant times $V_{bo}\delta/F$ to obtain the drag force at blowoff, in terms of blowoff velocity. Making this substitution, the drag force at blowoff is found to vary as the fourth power of the velocity, for a constant mixture ratio.

It was suspected that a similar relation between drag force and blowoff would exist for reverse jets. Therefore, the jet force at blowoff was computed from the gage pressure, and orifice area for the applicable data on reverse air jets presented in (1, 2). This force was plotted against the fourth power of the peak velocity at blowoff, which happens to occur on the rich side of the stoichiometric, at 125 per cent theoretical fuel, for both the propane-air mixtures of (1) and the methane-air mixtures of (2).

Received Dec. 2, 1956.

[1] Assistant Chief, Aeronautics and Thermodynamics Division. Mem. ARS.

[2] Numbers in parentheses indicate References at end of paper.

[2] Numbers in parentheses indicate References at end of paper.

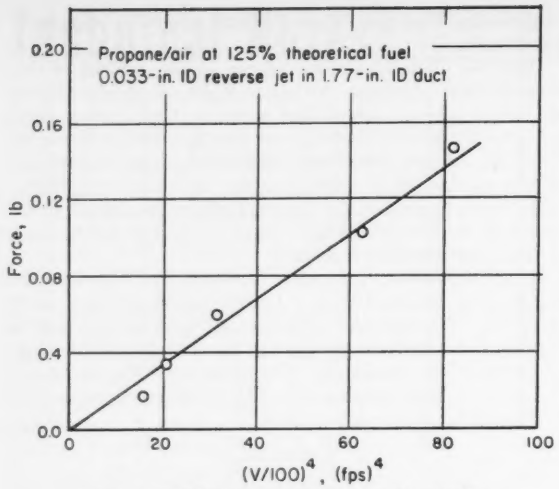

Fig. 1 Imparted force as a function of velocity (from Ref. 1, Fig. 4)

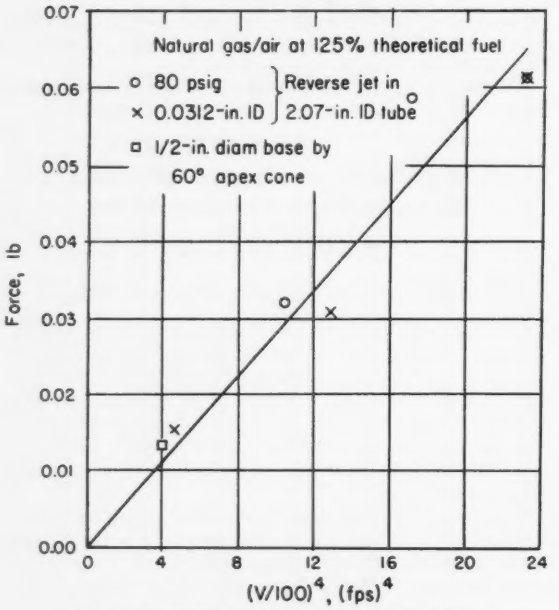

Fig. 2 Imparted force as a function of velocity (from Ref. 2, Figs. 20, 21)

Figs. 1 and 2 show the plots of these data. It is seen that, within the usual scatter expected from blowoff data, these data fall close to a straight line through the origin. Thus, it is apparent that the same general type of relation between blowoff velocity and minimum drag force at blowoff holds for both the reverse jet and obstacle-type flameholders. Such a correspondence of results would seem to indicate that there is a fundamental relation between the two mechanisms of flame stabilization.

In (2), some data were given on an axially symmetric obstacle used as a flameholder in the same combustor as had been used to study the reverse jets. From (4), the drag coefficient of that particular shape of obstacle, when used as a flameholder, is about 0.45. Therefore, it was possible to plot an obstacle blowoff point on Fig. 2, which is indicated by the square; the agreement with the line through the other data is good.

One other feature may be noted in the study of (1, 2). The mixture in the jet must be optimized for each over-all mixture ratio in the combustor to minimize the jet force at blowoff. For this reason, and because reverse jet and obstacle flameholding data should be obtained in the same system if they are to be compared, it was not possible to carry this present study further using the currently available data.

From the available data, it may be surmised that there is a minimum force which must be applied to hold a flame under any particular condition; however, this force might be applied in a variety of ways. Thus, it would appear profitable to take, as a basis for segregating the important and trivial factors in a fundamental investigation of flameholding, the point of view that the particular method of flameholding is unimportant.

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Effect of Turbulence on Flame Radiation

(*Continued from page 175*)

radical is formed at a time interval $\Delta\tau_{chem}$ before another radical, the time interval would appear spatially in the form of a difference Δx in the boundaries of the appearance of the two chemical species. In the case of the radiation-producing radicals these spatial differences could appear in the form of separations of the visible flame radiation. For example, as discussed previously, in an open turbulent flame brush the appearance of CH radiation preceded the appearance of the radiation due to the H_2O molecule by distances of from 2 to 10 mm.

The ideas presented in the preceding section can be pursued further. For a combustor that displays only a mild reduction in the values of $K_{F,\lambda}$ it can be inferred that the mixing time is considerably longer than the chemical time, and therefore the rate of release of energy is controlled by aerodynamics and not by chemistry. This is in agreement with the observations of Fenn (23), Longwell (24), and Barrere (25), that the steady-state energy release pattern of the "lightly loaded combustor" is nearly insensitive to velocity, pressure, and fuel type. At very low pressures (less than $^1/_2$ atm) it is probable that there will be an increase in the characteristic chemical times due to the reduction in the concentrations of the reacting gases. Therefore, since the characteristic mixing times can be expected to remain approximately constant (high Reynolds number flow) with decreased pressure, it can be expected that at low pressures the chemistry of combustion will again become predominant. This has been observed (24).

In conclusion, it can be said that the nature of the turbulent combustion process is becoming clear. The next major task is to put this information into a suitable theory for predicting the over-all rate of burning, particularly for ramjet-type burners.

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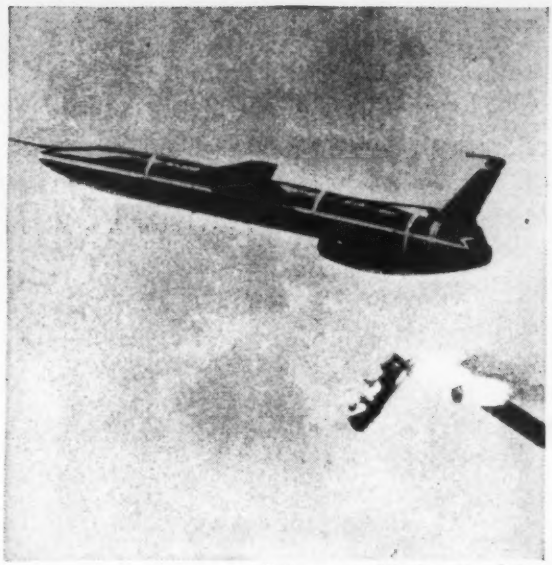

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Already approved by Congress, the first nuclear-powered, guided missile ship, a cruiser, is in the planning stage and will join the fleet probably in 1960. All major armament will be missiles. In addition to this and other nuclear-powered ships, the Navy has a number of conventionally powered guided missile vessels in the planning stage and on the way.

Meanwhile, the Navy is going ahead with the conversion of existing ships to guided missile carriers, already has some conventionally powered "G" vessels in operation. Briefly, this is how the Navy's missile arm lines up:

Surface-to-Air: Talos, largest of the three missiles to result from the Navy's Bumblebee Program (the other two: Terrier and Tartar), has been designated for eight cruisers. The first of these, USS Galveston, is now undergoing conversion and will be ready to join the fleet early in 1958. She will mount a Talos battery aft and conventional guns forward. Conversion of a second cruiser, the USS Little Rock, was recently assigned by the Navy. The last of the authorized Talos cruisers is scheduled for completion sometime in 1961.

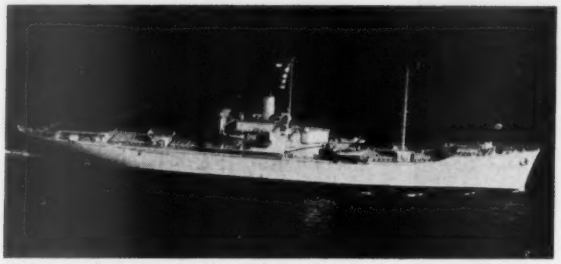
The smaller Terrier is already operational on the cruisers Boston and Canberra and the recently converted destroyer Gyatt. The three ships are equipped with twin Terrier launchers in addition to conventional armament.

Within five years, the Navy expects to have at least 19 more ships equipped with Terrier batteries. These will be mostly destroyers and frigates (larger and faster than destroyers), will carry missile launchers aft and conventional 3-in. and 5-in. batteries forward. Major function of these Terrier ships will be to provide antiaircraft defense for high speed (35 knots and above) task forces. But they will also participate in surface actions and shore bombardments.

Tartar, a smaller version of the Terrier, will be used on ships in the destroyer-size class replacing some conventional 5-in. gun mounts; it will serve as secondary antiaircraft armament on larger vessels. First Tartar installations are slated for ships in the Navy's 1957 building program. By 1962, says Rear Admiral James Russell, chief of the Navy's Bureau of Aeronautics, the Navy will have at least 17 Tartar ships in operation.

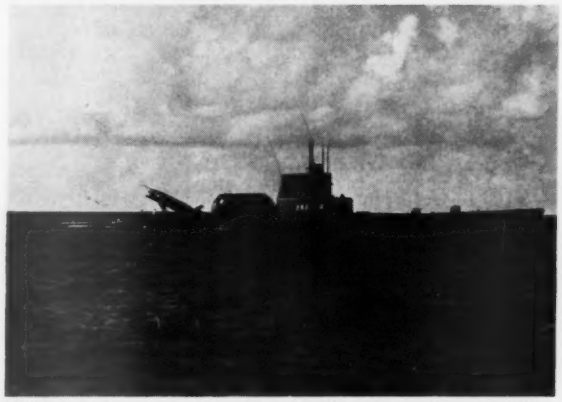
Kamikaze Offspring: Talos,

Missiles Give Fleet New Look

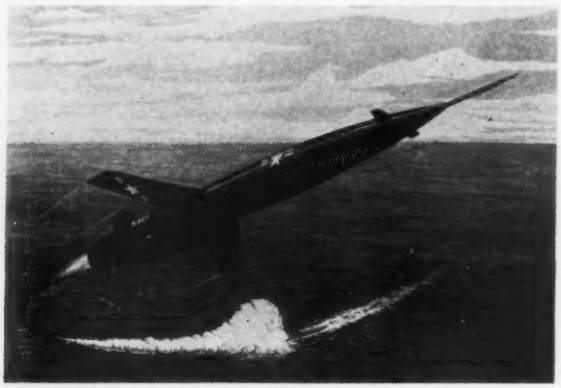


USS COMPASS ISLAND: She is the "forerunner of a fleet of nuclear-powered, ballistic missile-launching vessels."

PETREL air-to-surface missile enables Navy patrol bomber to strike from outside range of conventional antiaircraft defenses.

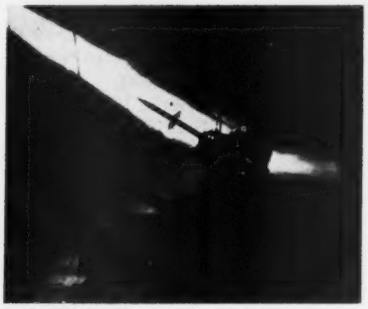


REGULUS I, surface-to-surface missile with nuclear capability, has rewritten the tactical role of submarines in future wars.

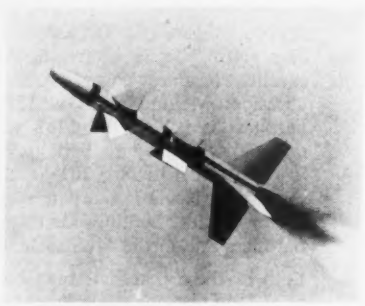


REGULUS II, shortly scheduled to become operational, is bigger, faster, and has a longer range than Regulus I.

USS BOSTON, firing Terrier I, is Navy's first operational "G" ship.

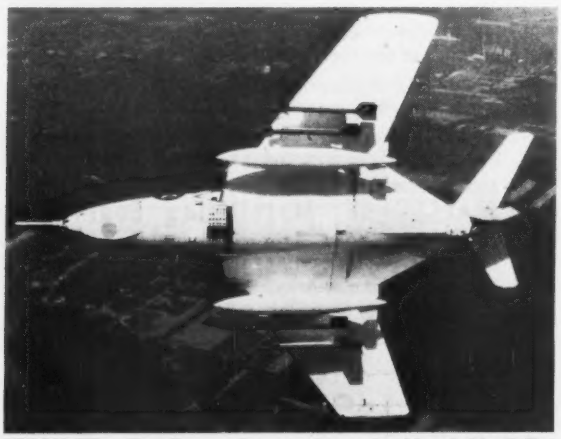


SUPERSONIC Terrier I is Navy's and Marine's first antiaircraft missile.



TALOS biggest of Bumblebee offspring, will join the fleet early in 1958.

FOUR Sparrow I air-to-air missiles, looking like off-colored offspring of parent Demon, give Navy fighters powerful punch.



BELLY-UP: Usually a soft spot, the underside of this F9F-8 Cougar nestles four deadly Sidewinder air-to-air rockets.

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Terrier, and Tartar are all products of the Bumblebee program which the Navy established in 1945 under the direction of The Johns Hopkins University Applied Physics Laboratory. Original purpose of the program was to counter the kamikaze threat of that time. Since the end of World War II, however, it has been directed toward production of missiles that can knock down supersonic aircraft before they get within critical range of fleet units.

All three are supersonic missiles. The ramjet-powered Talos, largest and most expensive of the three, first took to the air in 1952. In May 1954, it scored a direct hit on a drone at 25 miles. And, declares Admiral Arleigh Burke, chief of Naval Operations, there has been considerable improvement since then.

The smaller, rocket powered Terrier was fired experimentally in November 1954. Since then it has undergone extensive development; and, it is reported, there is a much improved Terrier II in the works. Beside installations on the Boston, Canberra and Gyatt, a mobile Terrier system is now in use with a Marine Corps anti-aircraft missile battalion.

A solid propellant rocket, the Tartar is the smallest and cheapest of the three missiles. It is boosted and sustained by a single rocket engine, reportedly has greater performance than the original Terrier.

Surface-to-Surface: Regulus I, of course, is the big "gun" in this group of missiles. About 30 ft long and resembling a swept-wing jet fighter, Regulus I flies at about Mach 1, has a 500-mile range, and is capable of carrying a nuclear warhead.

The missile, developed and produced by Chance Vought, first flew in 1950. Designed for launching from submarines, aircraft carriers, cruisers, and shore installations, the missile will be used principally against shore targets.

According to Admiral Russell, the Navy now has 10 ships set up for operational use of Regulus. Among them: submarines Tunny and Barbero; cruisers Macon and Los Angeles; and the aircraft carrier Hancock. (Many WW II cruisers, incidentally, carried a small seaplane hangar aft which now makes an ideal area for carrying the Regulus.)

In addition, the Navy has three submarines under construction—two, the Grayback and Growler, conventionally powered; the third, nuclear powered—designed expressly for guided missiles. The submarines will have missile hangars whose volume is almost as large as that of an entire WW I U-boat. All subs, of course, will continue to carry standard torpedos as well.

Regulus II will probably replace

IMPORTANT ACHIEVEMENTS AT JPL

Development of the Sergeant

Announced as a successor to the Corporal is another highly accurate surface-to-surface ballistic missile named "The Sergeant." This weapon will continue the United States Army's advance in the development of mobile firepower.

The latest techniques in guidance, airframe design and rocket propulsion are being applied to the development of this rugged weapon which is capable of operating in any area.

The Jet Propulsion Laboratory, designer of this new missile, has the same prime technical responsibility to provide the development of the complete Sergeant system as it had for the Corporal weapon system.

In addition to weapon development the "Lab" carries on supporting research in all areas related to guided missile work. These supporting research and weapon development activities complement and extend each other to produce superior end results.

This fact, coupled with ideal facilities and working conditions at JPL, is a prime attraction for scientists and engineers of unusual ability because of their close integration with such vital programs. At the same time, other varied and interesting activities in weapon development are providing new challenges and openings for qualified people.

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Regulus I before these new ships become operational. Already test fired, Regulus II is faster and has a greater range than Regulus I but is designed for the same operational use. Chance Vought recently received a $26 million Navy contract for production of both Regulus I and II.

Air-to-Air: Sparrow I, produced by Sperry, was the Navy's first air-to-air missile to become operational. It is now in service with squadrons of the Atlantic, Pacific, and Sixth Fleets. And at least one shore-based Marine night fighter squadron is also equipped with the bird.

A 1500-mph, solid propellant rocket, Sparrow I is about 12 ft long and weighs about 300 lb. Radar beam from the launching aircraft directs it to its target. Guidance signals deflect its wings, make it deadly accurate even against targets undergoing evasive actions. Sparrow is actually a family of missiles. But Sparrow I, the Navy says, is the only one now operational.

The Navy's other operational air-to-air missile, Philco's Sidewinder, is in service with squadrons of the Sixth and Seventh Fleets. A five-inch rocket with a small guidance section added, the Sidewinder is simple and cheap. It is the only missile, according to Admiral Russell, that can be produced at a price comparable to a load of aircraft cannon bullets. And, the Navy points out with pride, it's such a good bird that the Air Force is interested in using it.

Air-to-Surface: Navy's only operational missile in this field is Fairchild's Petrel. Designed to hit enemy ships below the waterline, it is launched by patrol aircraft, such as the P2-V, well out of range of target's air defense.

At the same time, the Navy states that it has other air-to surface missiles under development. One of the most promising is Eastman Kodak's Dove.

At one time, Navy men showed interest in the rocket-powered Shrike, an air-to-surface missile that Bell Aircraft was developing for the Air Force. Too small to meet payload demands, Shrike served as forerunner to the bigger Bell Rascal. Although the Shrike itself is no longer in production, there is still active interest in the vehicle's airframe design and guidance and propulsion systems.

The Big One: Technically in the surface-to-surface category, the 1500-mile Jupiter Fleet Ballistic Missile is actually in a class by itself. A joint project of the Army and Navy assigned to Chrysler, Jupiter will enable the Navy to reach any target on the face of the earth "from an infinite number of mobile launching sites."

Last December, the Navy moved a giant step nearer operational use of the FBM with the lauching of the USS Compass Island, a converted Mariner-class cargo vessel.

As described by Assistant Secretary of the Navy Garrison Norton, USS Compass Island "is the forerunner of a fleet of nuclear-powered ballistic missile-launching vessels, both submarine and surface types." Equipped with the newest and most precise navigational devices, the 17,600-ton ship is actually an experimental vessel whose mission is to provide a means of evaluating equipment for precise mid-ocean navigation without shore-based aids.

"We know the ballistic trajectory our missile will follow; we know the location of the target," explains Mr. Norton. "But to achieve success, we must know the location of our launching point to a degree of accuracy never hitherto attained at sea."

In an interview with *The New York Times*, last month, Mr. Norton disclosed the existence of another ballistic missile project the Navy is working on. The name of the missile is the Polaris.

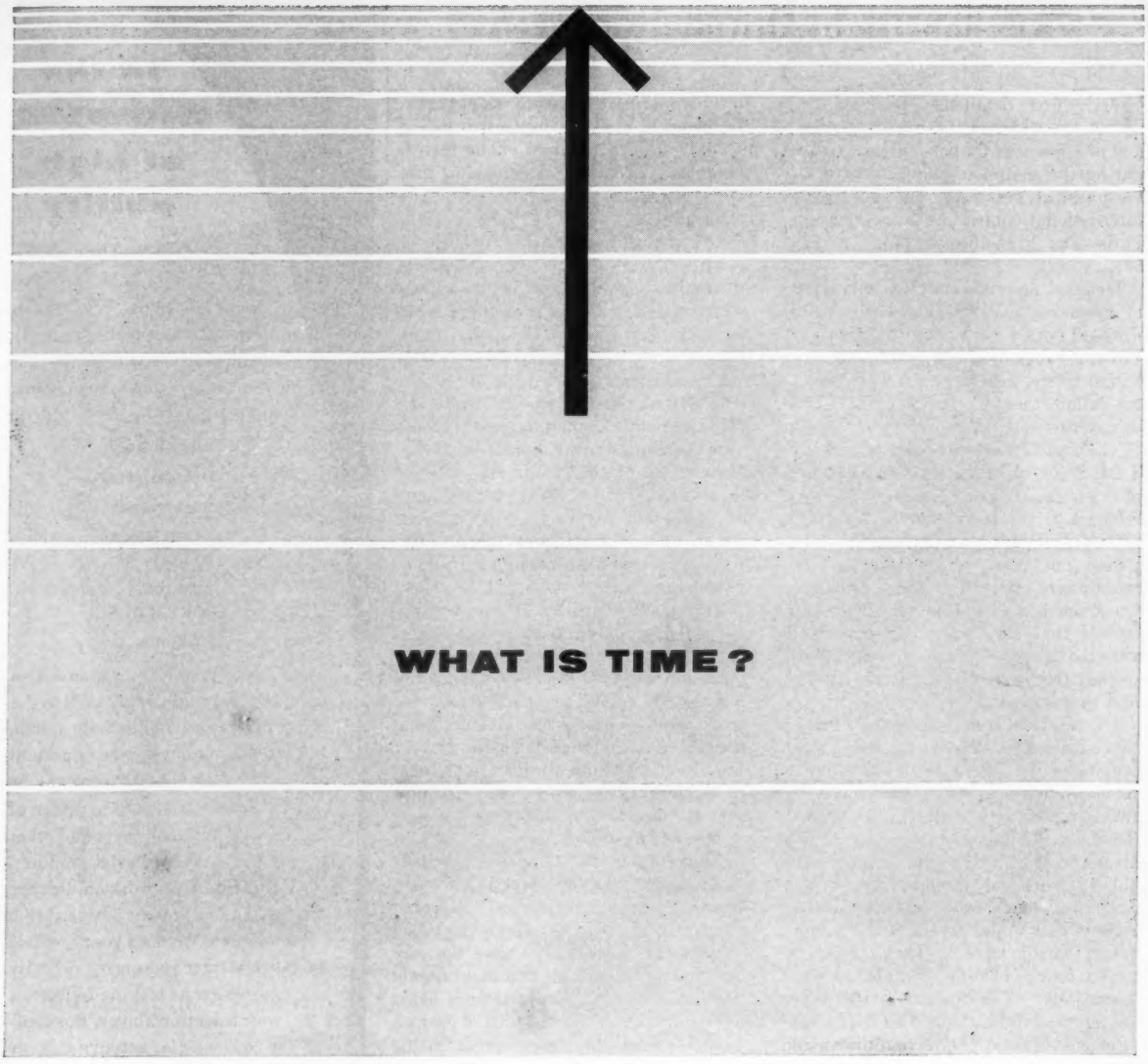
According to the *Times* interview, the Polaris is the Navy's replacement for the Jupiter. It will be fired from submerged submarines at targets hundreds of miles away. Presumably, it would be tailored for operation from projected nuclear-powered submarines and would also be adapted for launching from surface ships.

This new missile, Mr. Norton estimated, would be ready for operational use by the Navy in about five years.

Small But Deadly: A nuclear fleet is definitely abuilding. Nuclear-powered task forces are expected to be operational by the 1960's. As detailed by Navy Secretary Charles Thomas, one such force will consist of one or more nuclear-powered aircraft carriers, four to six nuclear-powered cruisers, and a limited number of nuclear-powered frigates. (Battleships, apparently, are considered obsolete. At present, there are only two in active service; and no mention is made of the big ships in future planning.) These ships will be armed almost entirely with missiles.

In addition, there will be nuclear-powered submarines of all types—attack, hunter-killer, supply, radar picket, and missile—fast enough to keep up with the high speed task force of tomorrow. But the most potent and promising role of the N-sub, according to Mr. Thomas, is as a guided missile ship.

"Just imagine a swift nuclear-powered submarine as a launching platform for a missile of 1200 to 1500 miles range. Imagine it going in fast, surfacing, firing its missile, then submerging and being gone. There's virtually no place in the world that it couldn't hit."



Anything that can be postulated is possible, says science—including *timelessness.*

The latest table-talk among the rocket and missile men has to do with the physics (and metaphysics) of photon propulsion: thrust for a space vehicle derived by shooting incredibly concentrated beams of light (photons) from its tail. Result—speeds approaching that of light! Round trips to distant galaxies could thus be accomplished in a single generation of the crew. Meanwhile, however, the Earth would have passed through a billion years—possibly into cosmic oblivion!

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Russian High Altitude Research

THE first detailed descriptions of Russian high altitude research work and of apparatus that she intends to use during the period of the International Geophysical Year came out in a recent international conference on rocketry in Paris (JET PROPULSION, Jan., pp. 57–58).

Detailed descriptions were also given of a series of experiments in which undrugged dogs were sent up to heights of 110 km in rockets and were then allowed to fall freely, in some cases to within a few kilometers of the ground, before parachutes opened.

The first of the two Soviet papers, by S. M. Poloskov of the Russian Academy of Sciences (Moscow) and B. A. Mirtov, referred to the possibility of flights to altitudes of 1000 km during the IGY period but made no mention of any intention to establish artificial satellites. Questioned about this, speakers answered that they were "not concerned with the nature of the vehicle employed" or that they were "just meteorologists" and that they had not been briefed.

Of possible significance in Russian plans for upper altitude research is their employment of self-contained canisters of instruments to make their measurements well away from the rocket proper. Telemetering techniques appeared not to be much in use. One member said this was partly because "not enough was known about the effect on telemetered signals that upper layers of the atmosphere would have." They prefer to make movie records of data, recover them later. The authors of the paper on physical research claimed that measurements of atmospheric conditions made by instruments within the rocket proper would not be satisfactory because the exhaust gases from the rocket give rise to a form of gaseous cloud around the rocket which of its very nature prevents measurement of parameters of an undisturbed atmosphere.

In the Russian work, an electrical measuring device is included in each circuit so that it can be continuously photographed. Exposed film goes into an armored container designed to survive even if parachute gear fails to function. The instrument containers are each 2 m long and 0.4 m in diameter and each weighs 250 kg. The lower part is hermetically sealed and contains batteries, milli- and micro-ammeters, the cameras, programming apparatus, clocks and all motors required to drive automatic devices in the upper part of the same canister. The upper part is not sealed and contains manometers, sampling globes of glass, and other devices that need to be in contact with the ambient air. A parachute is attached to the upper part but is, for safety sake, contained in a sealed protective casing of its own until required. The instrument canister carries a spike below that helps to maintain it in a vertical attitude when it lands.

To investigate the direction and speeds of winds a number of smoke generators are used. Each contains 5 kg of fumogenous material and is catapulted from the rocket by a "mortar" similar in design to those used to expel the instrument canisters. The firing is so arranged that the five smoke bombs explode more or less simultaneously at different altitudes between 60 and 80 km. Movements of the clouds are watched by cine-theodolites on the ground, using at least two for each cloud, spaced several dozen kilometers apart. The results so obtained are claimed to be of great precision.

The smoke particles themselves are about 0.5 microns in diameter and those at the higher altitudes begin to fall at once and disperse quickly. Those below the 80 km level are said to maintain themselves for a long time. The results showed that the wind velocities vary a fair amount but are always pretty high, of the level of 60–100 m/sec. In summer the direction is east to west and in winter north to south.

Space Canines. The second Russian lecture was by Alexi Pokrowsky, head of the Aero-medical Research Center near Moscow, and described experiments intended to pave the way for manned flight at altitudes around 100 km. He concluded that such flights were now possible but would not commit himself to saying when such flights would be attempted. The payloads already carried by the Soviet rockets to these altitudes suggest that such experiments need not be long delayed.

The flights with dogs were carried out in two phases. First, the animals were carried in pairs, each in its own hermetically sealed container in the nose of the rocket. The dogs were borne on specially constructed chassis. Each container, about 0.28 cu meters in volume, carried a system for regeneration of air. Other apparatus automatically measured temperature and pressure of air in the cabin and various parameters in the animals themselves, including blood pressure, frequency of respiration, and pulse. The comportment of the animals was also studied for some time before and after flights, and a continuous film record was made during the flight itself. Radio- and cardiographs were also made before and afterwards, and the simple conditioned alimentary reflexes were studied. In these initial tests nine dogs were used, three of them twice. They

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remained in the hermetically sealed containers for a total of three hours.

In the second phase the dogs, again borne on a specially designed chassis, had nothing to protect them except a "scaffandre," or diving suit, made for the occasion and carrying a plastic transparent helmet through which the dog could be photographed with the aid of an inclined mirror.

During both phases of the experiment one of the two dogs was ejected from the rocket at an altitude of 80–90 km and fell freely for 3 sec. Then the parachute opened, bringing the dog from about 80 km to the ground in from 50 to 65 min.

The second dog remained within the rocket, falling freely to a height of 35–50 km and a speed of 1000 to 1150 m/sec. Then it was catapulted out. The dog continued to fall free until its parachute opened automatically 3500–4000 m from the ground.

From this series of experiments, the author concluded:

- Space suits guarantee creation and maintenance of conditions necessary for life during rocket flight up to 110 km, during expulsion from the rocket, descent by parachute from a height of 75–85 km, and during free fall to within 3500 to 4000 m of the ground.
- The system of catapulting the animals from the rocket at heights of 75–85 km and at speeds of the order of 700 m/sec, and at heights of 35–50 km and at speeds of 1000 to 1150 m/sec assure the safety of the animals, maintenance of vital activities, and the absence of substantial modifications of physiological functions.
- The parachute system assures the complete security of descent and landing of animals equipped with space suits from heights of 75–85 km.
- A flight of short duration, say one hour, in the upper layers of the atmosphere does not provoke any "brutal" or substantial changes in the comportment of the animals or in the state and physiological function of their vital organs.

* * *

During the Paris conference it was also revealed that the Raven motor intended for the Skylark high altitude research missile (JET PROPULSION, Dec. 1956, p. 1112) had developed a fault which caused postponement of the first flight, scheduled for last autumn.

Little new material on propulsion came out of the conference. Boron hydride-type fuels did find a staunch supporter, however, in Glauco Partel, member of an Italian rocket firm, who described experiments carried out several years ago. He went on to say that fuels of this type could not be ignored by any country wishing to develop better propulsion units for air, submarine (especially torpedo) and surface work.

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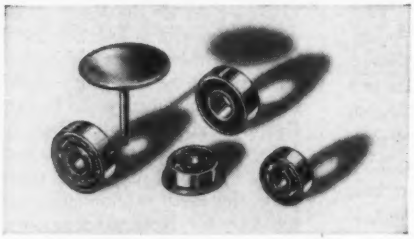

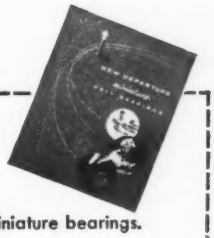

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General Motors Corporation
Bristol, Connecticut
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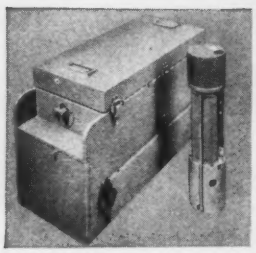
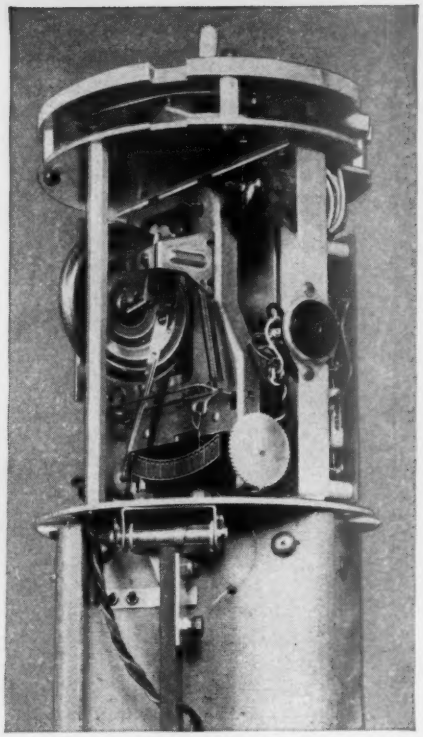
NEW DEPARTURE • DIVISION OF GENERAL MOTORS • BRISTOL, CONN.





ABOVE: Du Pont Rivets simplify "kid-glove" fastening on USAF's DROPSONDE. No backing, no after-finishing, no danger of damaging delicate mechanisms. AT LEFT: DROPSONDE, with its calibration box.

NO BACKING POSSIBLE, YET—

DU PONT RIVETS EASILY FASTEN DELICATE ASSEMBLIES IN STRATOSPHERIC "WEATHERMAN"

You're looking at the DROPSONDE: amazing new device manufactured for the USAF by the Friez Instrument Div. of the Bendix Aviation Corporation. Ejected from a "jet" high in the stratosphere, this electronic "weatherman" gathers and transmits temperature-pressure-humidity data back to the plane. There, a receiver-recorder takes over, interpreting and charting the impulses as DROPSONDE parachutes to earth. An accurate weather "snapshot" for flying missions and missile tests.

Since fastening's required within or around delicate mechanisms, *with no backing possible*—standard methods were "out." A knotty fastening problem, but the Baltimore firm found the answer in Du Pont Blind Expansion Rivets. Today, Friez workmen need fasten only from Rivet's head side—need only a heated iron to set 'em fast and sure—and mechanisms stay untouched. Takes only seconds, and these rugged fasteners stay put despite impact of landing.

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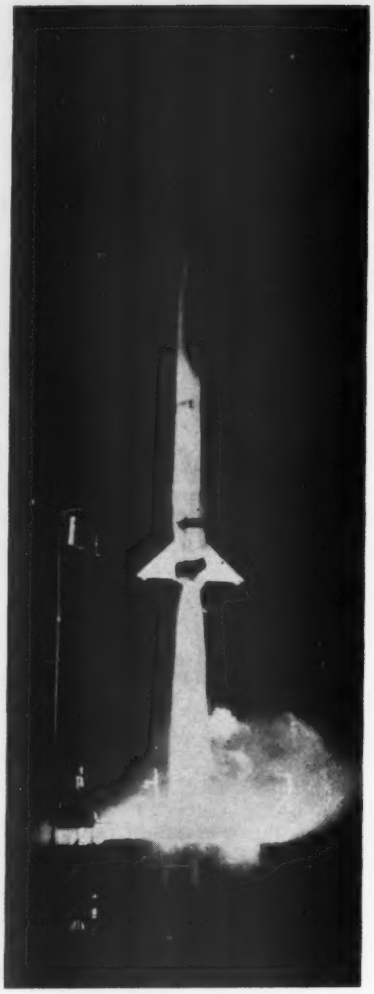


Viking No. 13 leads way as . . .

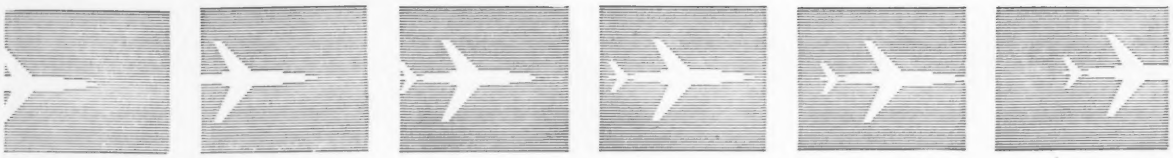
Satellite Program Takes to the Air

AT 1:03 a.m. on Dec. 8, 1956, the first test rocket of the earth satellite program took off from Air Force Missile Test Center at Patrick AFB (see JET PROPULSION, Jan. 1957, p. 57).

The rocket, thirteenth in the series of Vikings built for the Navy by the Martin Company, was fired for the purpose of testing instruments and gathering information to be used later in the satellite launchings during the International Geophysical Year (July 1, 1957–Dec. 31, 1958). The rocket was launched by the Navy's Project Vanguard which supports the earth satellite program sponsored by the National Academy of Sciences as part of the United States participation in the IGY.

After taking off from the launching platform, the Viking ascended a short distance vertically and then turned slowly toward the horizontal. The rocket reached a peak velocity of 4000 mph and climbed to an altitude of 125 miles, ending its flight in the Atlantic

ENGINEERS · SCIENTISTS



RECENT BREAKTHROUGHS IN SUPERSONIC AND HYPERSONIC KNOWLEDGE AND TECHNOLOGY— BASIS OF MAJOR RESEARCH AND DEVELOPMENT ACCELERATION AT REPUBLIC AVIATION

Alexander Kartveli, Vice President in Charge of Research and Development, Invites the Inquiries of High Calibre Engineers and Scientists

Recent discoveries justify a large scale, long range integrated attack on all the complex, interrelated aspects of passage through the upper atmosphere, in the opinion of Alexander Kartveli, creator of Republic's famous family of Thunder-Craft.*

Republic's R & D activities are now being materially augmented and accelerated to speed the exploration of this new knowledge and technology. The broad areas under study are:

- **Hypersonic and Satellite Weapons Systems.**
- **Advanced Propulsion Systems.**
- **Nuclear Energy Applications to Aircraft.**
- **Capabilities of Materials in Hypersonic and Nuclear Environments.**
- **Electronic systems development to exploit the full potential of the most radical concepts of flight.**

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MATERIALS

Please forward comprehensive resume in confidence to Mr. George Hickman Engineering Employment Manager

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The patented compound of Teflon used in *Fluoroflex®-T* hose makes it all the more unique. This compound imparts high tensile and tear strength, assures proper flex life, and a leakproof seal at couplings. With Fluoroflex-T hose you're *sure* of high integrity lines. Non aging, they're designed for indefinite storage life.

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CORPORATION • **Roseland, N.J. Western Plant: Burbank, Calif.**
Southwestern Plant: Dallas, Texas

Ocean about 180 miles from the launching base.

A Minitrack radio transmitter similar to the one which will be employed in the satellite was ejected from the rocket at an altitude of 50 miles and tracked by Navy scientists.

The rocket also carried telemetering equipment and tracking beacons similar to those planned for the satellite rockets.

After 450 sec of flight, the instrumented nose cone separated from the rocket and descended independently, telemetering information on temperatures and pressures it encountered.

Since the scientific earth satellites will be launched from the AFMTC, another important objective of the firing was to check out the newly installed launching facilities and ground equipment. The Viking which was fired was not a prototype of the 72-ft Vanguard rocket. But the first stage of the satellite vehicle will be a modification of the Viking. Hence, launching operations will be similar in many respects.

The thrust of the satellite first-stage rocket will be 27,000 lb, as compared to Viking's 21,000 lb. The weight of the three-stage satellite rocket before takeoff will be about 22,000 lb, while the 45-ft Viking weighs about 15,000 lb.

A second Viking test vehicle—reportedly the last of the Vikings—is scheduled to be fired shortly in connection with Vanguard preparations.

ENGINEER, AE

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Jet Propulsion News

Alfred J. Zaehringer, American Rocket Company, *Associate Editor*

MISSILES

• A B-57 jet bomber (photo) has been modified to test the "front end" of the Bomarc IM-99 missile. Boeing has revealed that the IM-99 has been successfully test fired in Florida. The tests included firings against drone aircraft.

• United States is negotiating for the installation of a missile tracking station on Fernando de Noronha Island some 150 miles off the northeastern coast of Brazil. The U. S. wants to station 60–80 personnel there but Brazil is to exercise military command over the volcanic island.

• A Regulus I recently went out of control, made a 120 mile dash across the Mojave Desert and crashed some three miles from the town of Ryan, Calif.

• Difficulties have been experienced in the flight testing of the Navaho cruise missile at the Florida missile test range. The missile was slated for a 2000-mile run but is said to have crashed on launching. New tests are to be held early this year. The cruise missile uses booster rockets for takeoff plus two ramjets for supersonic flight. Each ramjet engine is said to have a thrust rating of about 30,000–40,000 lb.

• Reliability of present guided missiles has still a long way to go, reflects R. P. Haviland of GE. Target to shoot for: a reliability of 4999 in 5000 must be developed and continued into mass production. This is comparable to driving a car for about 14 years without a flat tire or any other failure.

• The Air Force is setting up a special base at Camp Cooke (Lompoc, Calif.) to train men to handle its long-range ballistic missiles. The AF cautioned that this does not mean that the ICBM is ready. For example, they started training men two years in advance of receiving the Matador. Meanwhile, a special military board in Washington has been investigating vast Air Force missile and bombing ranges. According to the findings, some 14 million acres are now held by the Air Force. The board stated that about 5 million acres could be disposed of.

• Thor, IRBM prototype, is now in Florida for preliminary testing. First firing was slated for December 1956.

• Titan, ICBM by Martin, looks like it will be lox fuelled. Martin facilities at Denver and Patrick AFB will get large-scale lox generating plants. Aerojet is now developing the rocket powerplant for Titan.

• Navy has ordered 70 RP-70 rocket-propelled target craft from Radioplane Co. First batch of drones has been received and test fired. The target can hit an altitude of 50,000 ft and a speed of Mach 0.9.

• Another rocket-propelled drone, XKDT-1, is being built for the Navy by Temco. The low-cost, expendable rocket has sonic capabilities at altitudes over 50,000 ft.

• Dart, antitank missile under production by Utica-Bend Corp., is expected to become operational in about $1^1/_2$ years.

• New solid propellant, "Petrinacrylite," has been revealed by Rohm & Haas Co. Composition and performance is not known.

• Latest U. S. missile to hit the dust is the Army Loki AA rocket. The Northrop-Raytheon Hawk has been mentioned as the only AA barrage rocket project in operation. Hawk has 80-deg sweptback, short-span delta wings.

COMPANIES

• Marquardt Aircraft Co. has been designated as a prime contractor in the USAF Aircraft Nuclear Propulsion program. The ANP studies will be carried out at the Van Nuys, Calif., facility.

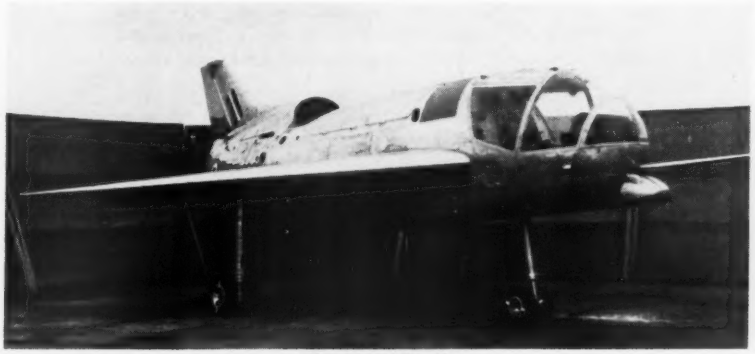
• Two new operating sections were established by GE's Missile and Ordnance Systems Div. A Nose Cone Section will concentrate on development of nose cones for the ICBM program. An Ordnance Section will handle all ordnance projects. The sections will operate in Philadelphia, Pa.

• Bomarc may be produced on a new site in the San Ramon Valley near Parks AFB, Calif. The Boeing Company already has an option to buy the Ford Motor plant at Richmond, Calif. Both facilities would be used to grind out the IM-99.

• Electronics for aircraft and guided missiles will climb to a whopping $1.5 billion business in 1957, predicts Minneapolis-Honeywell. Five years ago, automatic controls and instruments were about one-half of this price.

• Beckman & Whitley, San Carlos, Calif., has doubled its floor space for production of high-speed research cameras, meteorological instruments, and explosive actuated devices.

• To produce more plastic laminates for aircraft and missiles, Narmco Resins & Coatings Co., Costa Mesa, Calif., is spending nearly $\$^1/_4$ million to increase its output. Over the next three years, Narmco will spend an additional $1 million to triple its total capacity. Spotlighting the rapid developments in reinforced plastics is the formation of a joint industry-government effort for faster and more accurate development. The Reinforced Plastics Division of the Society of the Plastics Industry has formed the group which comprises over 200 companies. The Matador makes extensive use of structural plastics. The supersonic Hustler B-58 jet bomber is largely "glued" together with plastic adhesives.

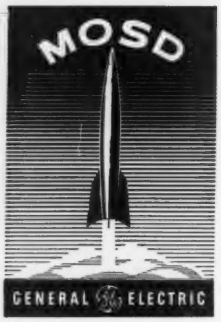


Going Up?

Powered by five Rolls-Royce R.B. 108 turbojets, Britain's first VTOL aircraft, the Short S.C.1, recently began taxiing trials. Once this phase is complete, the prototype craft will undergo vertical takeoff and landing tests and then the more difficult transition (from hovering to forward flight) tests.

Strictly a research vehicle, the Short S.C.1 will rise vertically, apparently like Bell Aircraft's VTOL, with the fuselage remaining in a horizontal position.

ENGINEERS & SCIENTISTS



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We would be pleased to receive a resume of your education and experience in order to arrange a personal interview with the manager of the appropriate technical area. Please address all correspondence to:

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MISSILE & ORDNANCE SYSTEMS DEPARTMENT
GENERAL ELECTRIC
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• Key personnel from Aerojet-General's Rotating Engine Dept. have banded together to form Turbocraft, Inc. President is Doyle Lindley. The firm will be located in the Pasadena, Calif., area and will design and develop turbines and turbopumps for aircraft and missiles.

• Three blowdown-type research wind tunnels are in use by United Aircraft Corp., East Hartford, Conn. Ranges of the tunnels: transonic (Mach 0.5–1.5), supersonic (Mach 1.5–5), and hypersonic (Mach 0.5–10).

FOREIGN

England. Scarab RATO unit puts out a short peak 6000-lb thrust which then drops to 3500 lb. The burning time is about 6 sec for the cordite charge.

• Development on the Armstrong-Siddeley "Screamer" rocket motor has been stopped. Reason: lack of suitable research craft and growing U. S. hardware for rocket aircraft. First tests of the British liquid engine were made in March 1954 with the project coming to a halt in December 1955. The throttleable, lox-kerosene, water cooled motor had a thrust range of 800–8000 lb. Turbopumps were driven by propellant-fed gas generator. Specs: dry weight, 470 lb; length, 78 in.; package diameter, 28 in. An I_{sp} of 200 sec was obtained at a thrust of 6000 lb. Highest thrust reached in static tests was 8900 lb while an engine chalked up a stand run of 8000-lb thrust for a total of 3 hours.

• Napier Flight Development Establishment, Luton, England, has designed a series of 5 peroxide rocket motors for helicopter rotor tip propulsion. The smallest unit delivers 25-lb thrust with a motor weight of 1.04 lb. The unit features a curved exhaust nozzle, catalytic decomposer; propellant feed is by centrifugal force.

• Fireflash, the British air-to-air weapon, is said to have knocked down target aircraft in a recent demonstration. The missile is $7\frac{1}{2}$ ft long and has a diameter of 6 in. Powered by two solid propellant boosters and one sustainer, Fireflash is being produced in test quantities.

• Armstrong-Whitworth has revealed a test vehicle which simulates a missile it is now developing for the Royal Navy. The fuselage, a finned, wingless dummy, is propelled by three solid rockets.

• Bristol has shown its twin-ramjet missile. The ramjets are mounted on the end of short wings. Four solid propellant booster rockets are used to launch the test vehicle.

• English Electric has fired a ground-to-air missile of 15-in. diam and 20-ft length.

• Napier is currently testing a ramjet missile launched by four solid rockets.

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by Reeves INSTRUMENT CORPORATION

helps USAF BOMBING CHAMPIONS set new record

Strategic Air Command's annual Bombing-Navigational competitions are the "World Series" of bombing tests. B-47 teams from Strategic Air Command bases throughout the country, flying thousands of miles in simulated bombing runs, performed remarkable feats of navigation and precision bombing. The culmination of long months of ground and air training, the bomb scoring results obtained were the best in the history of the competition. SAC teamwork, highly trained crews, and the most advanced navigational and bombing equipment all contributed to the gratifying results obtained.

Data for determining the accuracy of the bombing runs was computed by the MSQ type of Command Guidance System, designed and built by Reeves Instrument Corporation. Tracking by radar, the system provides a continuous plot of the plane's ground position. The point of bomb release is plotted, and from it the point of impact determined to a very high degree of accuracy. The MSQ type of system can also be adapted to Command Guidance of fighter bombers for close support bombing and strafing of enemy positions.

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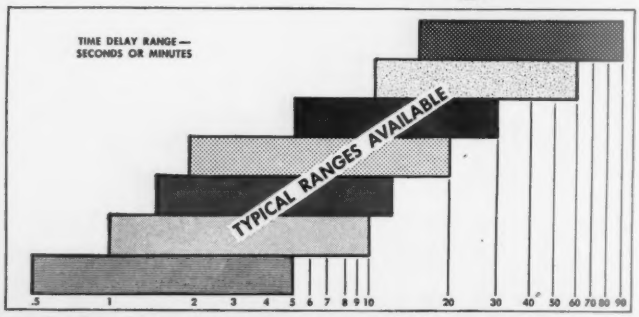

Shown in the chart are typical ranges available in these units. Special ranges frequently can be supplied to meet specific requirements.

Write for Bulletin AWH TD401

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• The Royal Aircraft Establishment is checking out a missile at Aberporth, Wales. Boosted by 8 cordite rockets, the sustainer motor uses concentrated hydrogen peroxide. The rounds are similar to those being supplied by Short and Harland in Belfast.

Sweden: Bofors firm is reported to be working on a novel antiaircraft missile for submarines. The weapon is said to be fired against aircraft while the sub is still submerged.

Russia: During the recent Suez crisis, Russian leaders threatened to rain nuclear-armed missiles against Britain and France. Sources in the U. S. have stated that the USSR is firing several 900- to 1000-mile-range rockets per week in ranges in Siberia and Eastern Ukraine. In the Anglo-French entry into Egypt, a large number of new-design rocket guns were found. The Soviet recoilless antitank weapon of 85-mm caliber was seen for the first time.

RESEARCH & DEVELOPMENT

• An ultra high-speed printer-plotter that can translate the lightning-fast language of an electronic computer into easily printed records as fast as the brain can calculate is being used at Aberdeen Proving Ground to process ballistic missile data. Designed for the Ballistic Research Laboratory by Burroughs Corp., Detroit, the BEPOC (Burroughs Electrographic Printer-Plotter for Ordnance Computing) is used in connection with ORDVAC. Speed: 300 plotting points per sec. Next job for BEPOC-ORDVAC may be to process "in flight" data from the 80 rockets to be fired at Fort Churchill and the Vanguard satellite program during the IGY.

• Atlantic Research Co. will begin construction this spring of a new $1-million office and research facility in Fairfax County (Va.).

• Boeing Airplane Co. will use Beckman IR-4 infrared spectrometer in its study (for the Air Force) of special emission characteristics of various metals and high temperature-resistant coatings at temperatures to 1400 F.

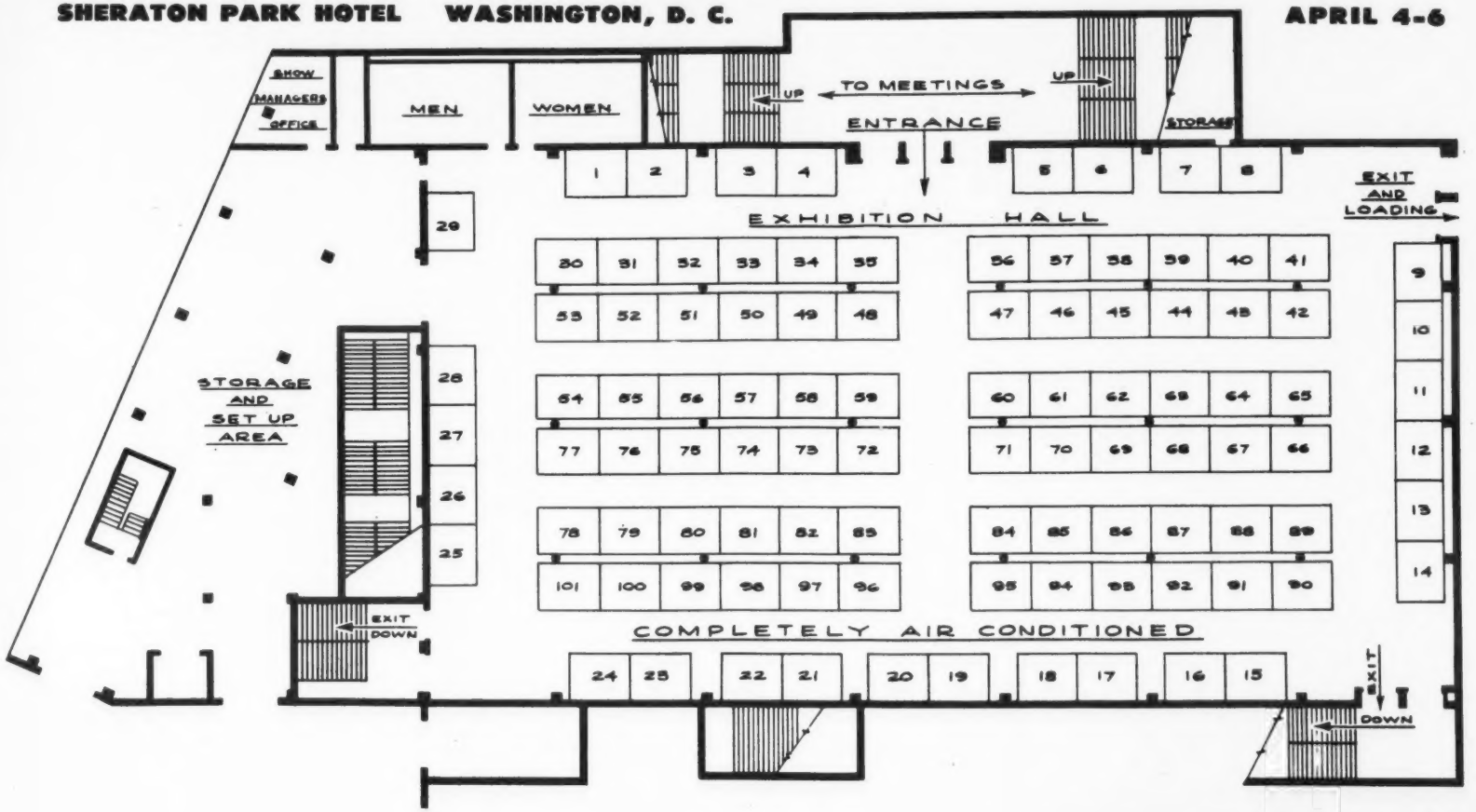
• Another brain for guided missile development is an $8 million device to be used by USAF at Holloman AFB by 1958. The "real time" closed loop analysis system is to be used to reduce data from the first few minutes of a missile's flight and compare it with estimated performance. In this manner it will be possible to transmit new instructions to the missile while still in flight.

• How to handle data will be demonstrated at Western Reserve University, Cleveland, Ohio. The University Cen-

AMERICAN ROCKET SOCIETY

SPRING MEETING AND ROCKET AND SATELLITE EXPOSITION

SHERATON PARK HOTEL WASHINGTON, D. C. **APRIL 4-6**



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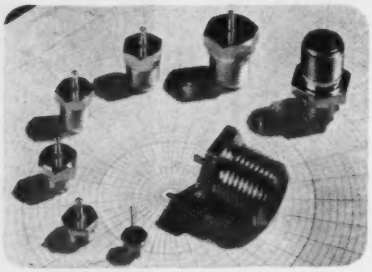

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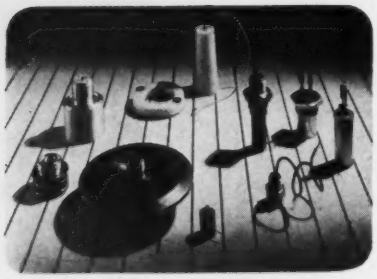
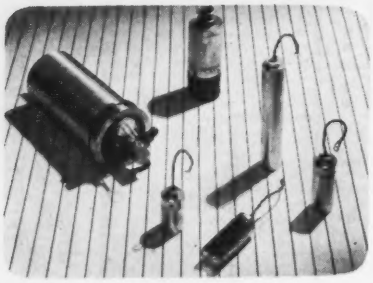


TYPICAL IGNITERS include styles with integral or threaded-in squibs in configurations to meet specialized requirements and include completely frangible types, rear.



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ter for Documentation and Communications Research will demonstrate systems for organization, storage, and retrieval of recorded information on April 15–17, 1957.

• The Air Force Office of Scientific Research has awarded contracts to Aerojet and Phillips for research on free radicals as a possible propellant source. In addition, the National Bureau of Standards has established its Free Radicals Research Section which will be monitored by Army's Office of Ordnance Research.

• The Armour Research Foundation revealed that an Air Force physiologist survived after breathing a concentration of 8 ppm ozone for one hour. Results were that, in sensitive persons, as little as 2 ppm of ozone in air may cause severe lung irritation in less than 1 hour. Swelling of lung tissue seems to start at about 4–5 ppm. Also found was a definite impairment of the sense of smell. Interest in ozone toxicity stems from the layer of ozone that pilots will encounter when they penetrate the upper atmosphere.

Japan's 'Baby' Rockets

STEP by step, Japan is moving ever deeper into the rocket business. Only two years old, the Japanese research rocket program has evolved from the half-pound Pencil rocket to the 88-lb Kappa 128 JT (see JET PROPULSION, Nov. 1956, p. 994). Next step is a multiple-stage IGY research vehicle based on a Kappa-type mainstage rocket.

In addition, Japan has produced its first military missile, the solid propellant TMA-O-AC, and has a second and larger missile, the TMB, on the way (JET PROPULSION, Oct. 1956, p. 893).

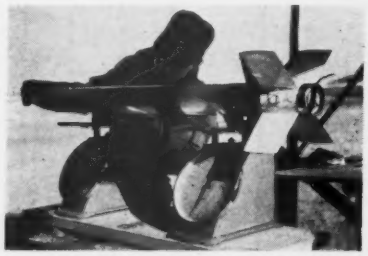
Significant Steppingstone: One of the most important phases in this comparatively rapid development centered about a group of solid propellant rockets called the "Baby" series.

In January 1955, Japan organized a Special Committee for a Sounding Rocket Program under the leadership of Hideo Itokawa, professor at the Institute of Industrial Science, University of Tokyo. The committee first investigated basic rocket vehicle design parameters with small solid propellant rockets, measuring 9–18 in. in length and weighing 0.42–0.75 lb. Dubbed Pencil rockets, they were fired on horizontal and vertical test ranges to obtain velocity, stability, and control data.

When sufficient data had been collected, larger solid propellant rockets were built and tested. These were the Babys.

S for Simple: The Baby-S (Simple) rocket was designed for further studies in launching, stability, and control. Six Baby-S rockets were launched in August 1955 from a tower having a guide length of 13.5 ft. The Baby-S sustainer motor developed a thrust of 246 lb with 1.605-sec burning time. Velocity was approximately 330 fps. The length of the rocket, including booster, was 3.92 ft; diameter, 3.15 in.; fin span, 11.8 in.; weight, 15.85–18.4 lb.

The Baby-T (Telemeter) was designed to investigate the problems of telemetering. Temperature, pressure, velocity, and acceleration were measured and transmitted to the ground station from these rockets. Five Baby-T's were launched Sept. 17–24, 1955. The rockets were launched from the tower at an angle of 70 deg. Length, including booster was 4.4 ft; diameter, 3.15 in.; fin span, 11.8 in.; weight, 20.5 lb; altitude, 6000 ft.



BABY-R is mounted on scales to determine the center of gravity.

Realizing that all rockets would have to be launched over the sea due to lack of land sites in Japan, the committee decided that physical recovery would have to be investigated. This was to be the role of the Baby-R (Recovery) series. The nose section of the Baby-R contained a 16-mm movie camera, which was ejected, and recovered by a parachute. A float, which automatically inflated when the parachute opened, and a dye sea marker completed the rocket's payload. Three Baby-R's were fired during November 1955. Baby-R No. 3, launched at an angle of 72.5 deg, attained an altitude of 6550 ft and exceeded 370 fps. Movies taken from the rocket during this flight and payload recovery were highly successful. Length, including booster, 4.75 ft; diameter, 3.15 in.; fin span, 11.8 in.; weight, 19.9–20.1 lb.

The Baby rockets were manufactured by Fuji Precision Machinery Company. Japan's first post-war military missile, the TMA-O-AC, is a direct descendant of the Baby rockets.

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Scientific Research in the Soviet Union

R. E. MARSHAK[1]

THE "new look" in the Soviet Union since the death of Stalin has probably had a greater impact on science than on any other field of human endeavor. It appears that there has been a tremendous improvement in the scientific climate in the U.S.S.R. and that, to a considerable extent, freedom of science has been re-established there. I should like to make it clear that when I refer to Soviet science, I am thinking chiefly of physics, the field in which I work and in which I made most of my observations during my recent visit to the Soviet Union.

Scientific Freedom

The significant changes that have taken place since Stalin's death, particularly as they bear on scientific research, are as follows.

1 It seems that all scientists who were formerly in disgrace or under arrest have been rehabilitated and that all the brilliant scientists who had been in trouble have been returned to positions of leadership. An excellent example is the case of Kapitza, an outstanding physicist, who was placed under house arrest for 7 years when he refused to work on atomic weapons research. Kapitza was released soon after Stalin's death and is now back as director of the Institute of Physical Problems in Moscow at the same high salary (30,000 rubles per month) as the president of the U.S.S.R. Academy of Sciences, the most powerful scientific body in the Soviet Union.

2 All the usual scientific channels of communication are now open, including the exchange of scientific and technical information with foreign scientists.

3 Personal contact with foreign scientists is now allowed. Soviet scientists are permitted to attend international conferences outside their own country, and foreign scientists are invited to attend scientific gatherings in the Soviet Union and to visit Soviet laboratories.

4 The rigid mobilization of Soviet scientists to work on war projects has apparently been discontinued. For example, Soviet physicists are no longer required to work on radar, rockets, or nuclear weapons; they are permitted to concentrate their energies in such a pure nonmilitary field as high-energy nuclear research.

5 A much more liberal policy of declassification of scientific research has been adopted. The results of basic research in such fields as nuclear physics can now be freely published in scientific journals. Indeed, in some fields such as controlled thermonuclear fusion, Soviet policy has been more liberal than United States policy. On the other hand, in such a field as that of electronic computers, Soviet security regulations are still much stricter than ours.

6 Soviet science is much less nationalistic now than it was in the Stalin era. It is no longer claimed that all the important scientific discoveries are of Russian origin (which they are not), and it is no longer necessary for Soviet scientists to publish their papers exclusively in Soviet journals and to use the Russian language.

7 There has been a considerable devaluation of Marx's philosophy insofar as pure science is concerned. For example, in biology, Lysenko is no longer political czar of Soviet genetics. In the more abstract science of physics, no lip service of any sort seems to be paid now to dialectical materialism and its alleged indispensable role in the development of physical science. In our discussions of physics at the Moscow conference, we Americans and our Soviet colleagues spoke the same language.

8 Freedom of criticism in science is accepted as a virtue. There was vigorous and uninhibited discussion at the Moscow physics conference, the young Soviet physicists did not hesitate to call to task distinguished academicians if points of difference arose.

Lack of Political Freedom

I can go on in this fashion, but I believe that it is evident that many of the ingredients of scientific freedom now exist in the Soviet Union, certainly as far as physics is concerned. The reemergence of scientific freedom is not to be confused with political freedom in which there has been some slight improvement in the U.S.S.R. but in which there is still a very long way to go. After all, the government of the Soviet Union is still in essence a dictatorship, a collective dictatorship if you will, but still a dictatorship. The Supreme Soviet only meets 4 or 5 days at a time, twice a year, just as it did in pre-Stalin days, and it is no more a true legislature than it was before. There is still only one party in the Soviet Union, there is no freedom of assembly, censorship continues, Lenin has replaced Stalin as the great authority on all matters of public policy, and so forth. However, the naked terror of the Stalin regime with its mass arrests, its complete isolation, its vindictiveness and singleminded suppression, and its great suspicion of and hostility to the West *appears* to have ended. Because of the failure thus far to achieve a genuine democratization of Soviet society with its concomitant built-in guarantees of permanence, the situation is an unstable one, and one cannot be certain that a new Stalin will not arise. However, it is clear that the Khrushchev smile is not solely for foreign consumption; there are observable changes associated with it as far as the general populace is concerned and, in many ways, there are remarkable changes resulting from this smile in the scientific domain.

The rebirth of scientific freedom in the Soviet Union is not tied in with any commensurate increase in political freedom and may have only a temporary basis, but the fact is that it now exists. It is now possible for a Soviet scientist to choose the subject matter of his own research and to draw the conclusions to which his investigations lead without subjecting them to the requirements of some nonscientific authority. However indispensable as are these moral and spiritual factors in the development of a healthy science, scientific research will not prosper in the present day and age without powerful material support.

Financial Support

The U.S.S.R. is sparing no effort to provide the necessary financial support for scientific research. This effort consists of providing both financial and prestige incentives to qualified students in science and engineering and also of providing funds for a very large technical and educational plant. The stipend of a Soviet graduate student exceeds the salary of an unskilled worker, and the salary of a distinguished scientist in the Soviet Union is as much as 50 times the salary of an unskilled worker. Prestige incentives are equally as great. One of the great honors for a scientist in the Soviet Union is to be elected to the Academy of Sciences, a body which plays a dominant role in the direction

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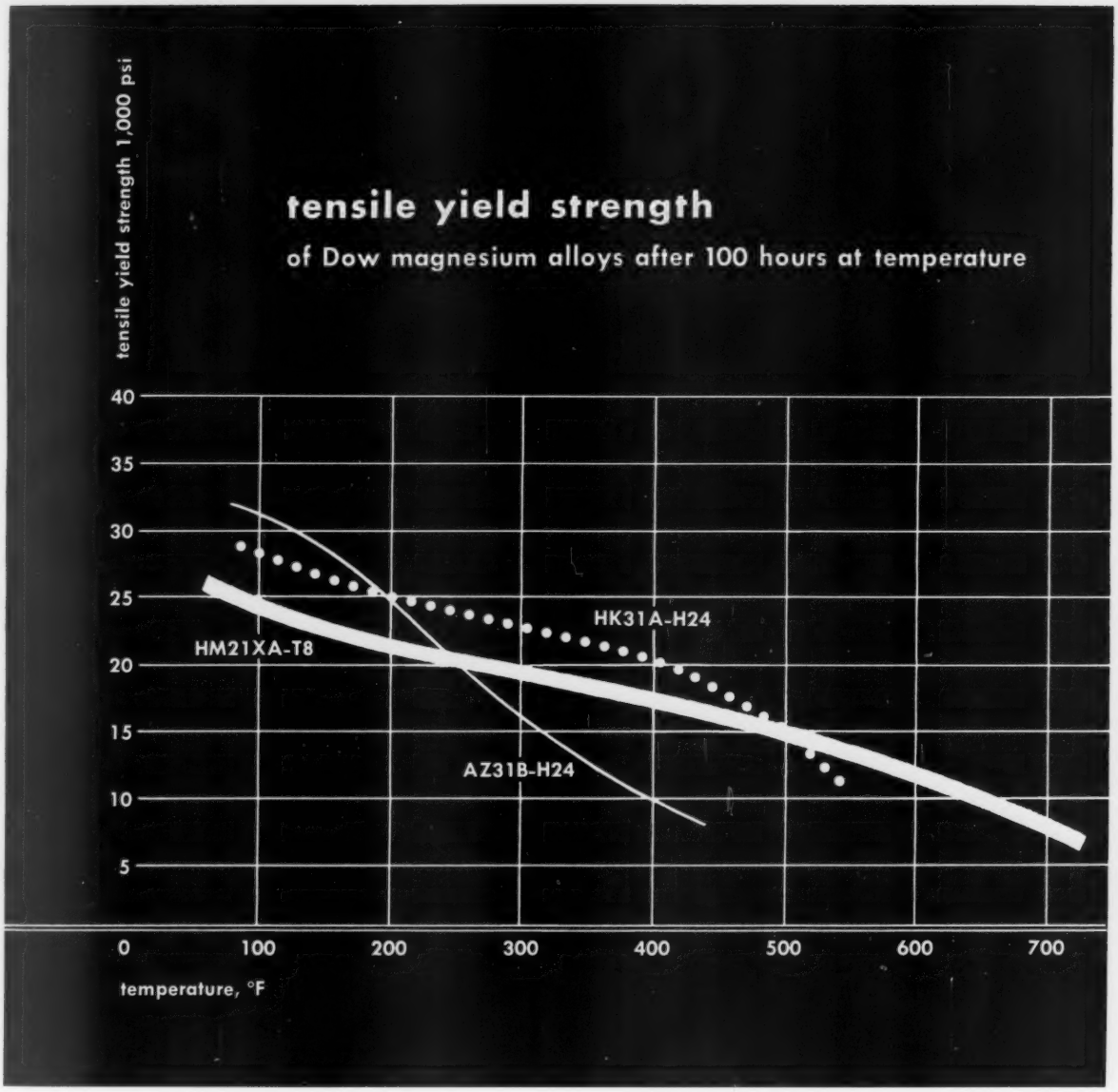
[1] The author is Harris professor of physics and chairman of the department at the University of Rochester. This article is based on a talk given before the Research Committee of the National Association of Manufacturers, which met in New York on 19 Oct. 1956. The author attended the Moscow Conference on High Energy Particles held 14–22 May 1956 as a member of the American delegation.



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and support of scientific research. The honor of belonging to the U.S.S.R. Academy of Sciences is coupled with a financial remuneration equal to 10 times the salary of an unskilled workman. As a result of this policy, scientists form an élite whose scale of living—although not outstanding by American standards—stands in extreme contrast to the still low living standards of the general populace. It is therefore not surprising that of the 16,000 students at Moscow State University, 2000 are majoring in physics.

In addition to providing major financial and prestige incentives to scientists and engineers, the Soviet Union has developed an educational and technical training system with excellent facilities and high standards. Indeed, in some areas, the standards are higher than they are in the United States. For example, the average Soviet electrical engineer takes more mathematics and basic physics in his curriculum than his American counterpart and as a result appears to be more independent, creative, and critical than the average American electrical engineer. As a special twist in the whole situation, these highly talented engineers receive higher salaries and enjoy more prestige in laboratories where basic research is done than they do in an industrial setup. During my visit to the Soviet Union, I was greatly impressed with the close collaboration that exists between physicists and engineers in research laboratories. In my own field of high-energy nuclear physics, many of the papers on fundamental accelerator design, topics which in the United States are still the exclusive concern of physicists, were delivered at the Moscow conference by engineers.

The close attention which the Soviet government is paying to the support of scientific research is manifest not only in the attractive salaries paid to its scientists and engineers and in its insistence on high standards in higher education, but is also demonstrated by the lavish provision which it makes for new up-to-date laboratories and the most modern experimental equipment. It seems that scientific research in the Soviet Union is being pursued with an urgency which is reminiscent of a wartime operation. As my colleagues and I toured the nuclear research laboratories in the U.S.S.R. last May, we noted the same personal dedication to the task at hand, the same emphasis on speed rather than cost, the same unlimited financial support for facilities and equipment which we ourselves had known at Los Alamos during World War II. It seems clear that the scientific research program in the Soviet Union is gathering enormous momentum and that the objective is to overtake American science in its great diversity, its high quality, and its magnificent sweep.

The fruits of scientific research in the Soviet Union have been the rapid industrialization of the country and the development of a modern technology which, in many ways, is second only to that of the United States. However, a strange dichotomy exists in the U.S.S.R. Although there has been remarkable progress in industrialization and technology, the developments have had relatively little impact on the general standard of living. Indeed, it appears that to a very great extent the astonishing speed of industrialization and technologic innovation has been made possible by withholding its benefits from the people at large. It seems that the lot of the common man in the Soviet Union will not be greatly improved until heavy industry and advanced technology have achieved a level comparable to that in the U.S.

From what I have said, it follows that scientific research in the Soviet Union has a potential for great achievements. Not only have the moral and spiritual conditions for independent and creative research been greatly improved since Stalin's death, but the material support is as great as it was before, if not greater. These factors, with their resulting high morale among the scientists, plus the excellence of scientific training, plus the education of the public on the value of science, will unquestionably lead to an efflorescence of Soviet science and to strong competition with the United States.

Meeting the Challenge

I believe that the challenge can be met in our own American pragmatic way without adopting the centralized control of scientific research which is part and parcel of the Soviet system. Scientific freedom already exists in the United States and indeed has existed for a long time. There is an occasional lapse such as Secretary of Commerce Weeks' dismissal of the director of the National Bureau of Standards in connection with the battery additive incident or former Secretary of Health, Education and Welfare Hobby's withdrawal of Government funds from medical researchers in whose files some derogatory information was found. But, by and large, the American scientist has been free for a long time to choose the subject of his own research and to publish his results without approval by a nonscientific authority. As far as material support of science is concerned, there has also been much improvement during the past decade.

But the whole point of my remarks is that the Soviet scientific challenge underlines the importance of a frank reappraisal of the scientific picture in

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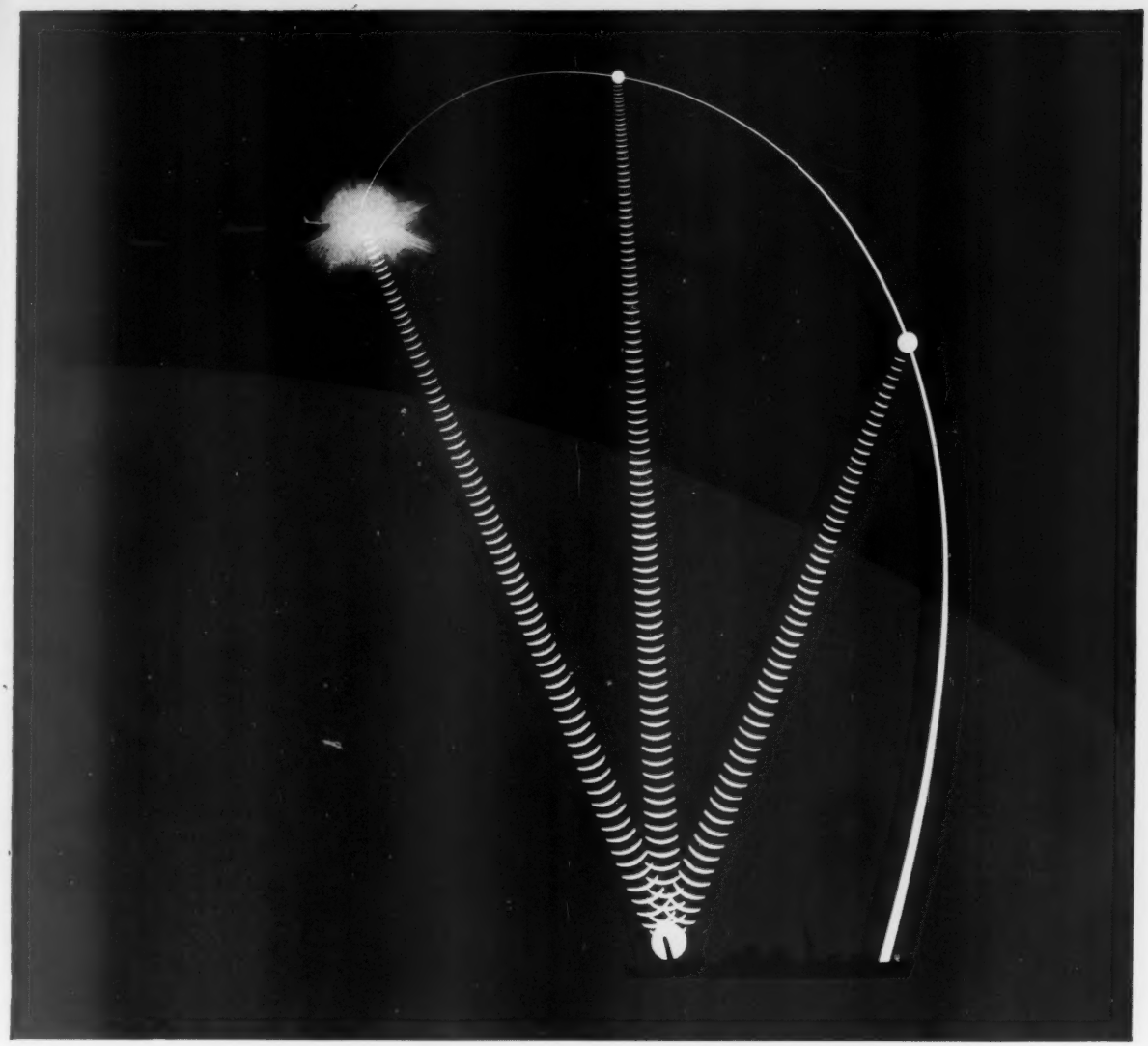

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our country, a reappraisal that in any case is long overdue. I believe that all responsible Americans will draw the necessary conclusions from the new situation in the Soviet Union. However, I should like to list several of my own conclusions to indicate how the quality and productivity of scientific research can be improved in the United States.

It seems to me that the financial and prestige incentives in this country are not such as to persuade the scientist or engineer to remain at the university where most of the basic research is done and where all the training of new scientists and engineers takes place. I believe that American industry might do well to ponder the possibility of subsidizing greatly increased salaries of a sizable number of outstanding scientists and engineers who remain at their university posts and continue their teaching and basic research programs. As far as our educational standards are concerned, the quality of scientific training in our graduate schools is of high quality, but the same cannot be said of the quality of training of our engineers or of scientific training in our high schools and colleges. Improvements along these lines can be achieved if sufficient funds are made available by all levels of government and industry to train better teachers and to keep these teachers in the high schools and the colleges, to re-examine scientific and engineering curriculums, to educate the American public on the value of science and engineering, to provide financial support for *all* young people who desire to embark on scientific and engineering careers, and in many other ways. It is also essential for American government and industry to provide the increasingly large sums of money which are required to carry on basic research in the sciences in this, the middle of the 20th century. Finally, it seems to me too that American industry must re-examine the use to which it is putting its scientific manpower: Are engineers being utilized to the full extent of their intellectual resources, or are they being placed in inferior and less productive positions? Can basic research programs that are now being started up in industrial laboratories be undertaken more profitably by throwing the equivalent financial support to high-quality university laboratories where at the same time the scientists are reproducing their own kind—that is, developing new scientific manpower?

I am convinced that all these and many other things can be done without losing the essential ingredients of the scientific freedom which now obtain in the United States and without impairing the research that must be carried on

(*Continued on page 209*)

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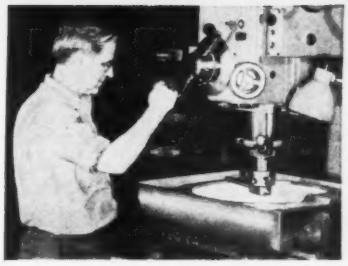

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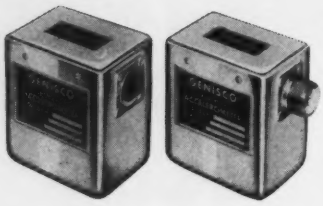

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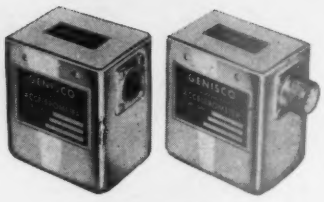

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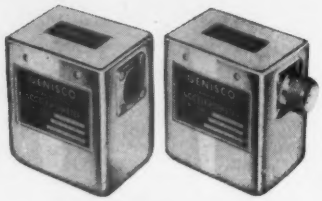

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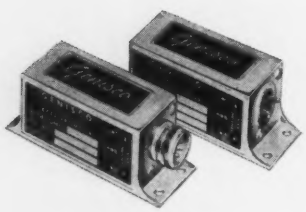

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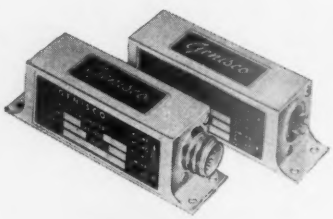

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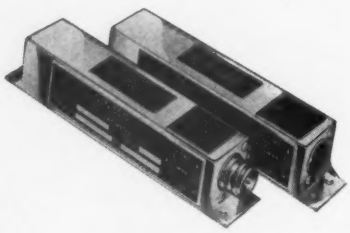

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Meteoritic Dust

Introduction

THE present knowledge of the abundance and energy distribution of meteoritic dust is limited. The main reason for this is the difficulty of investigation. Dust of terrestrial origin is found up to twenty kilometers, indicating that research vehicles must at least exceed that altitude.

Balloons offer themselves as the best research vehicles for stratospheric altitudes, while artificial satellites may prove superior for the exospheric studies. The gap between is inadequately filled out by sounding rockets, capable of attaining high altitudes but unable to remain aloft.

The information on meteoritic dust is obtained mainly from photographs of meteor trails with the Baker-Schmidt camera, and by radar reflection techniques. Other methods are filtering of rain water and capture of dust particles on sticky plates. During the spring of 1957, a Skyhook balloon equipped with altitude-regulated sticky plates will be launched to capture meteoritic dust particles without terrestrial impurities (1).[1]

Terminology

Confusing names have been given to the interplanetary matter reaching the earth, such as cosmic dust, shooting stars, interplanetary dust, meteor stones, and others. The following may clear up the terminology:

Meteorites are hard, solid, high density materials. They may penetrate the atmosphere and hit the ground, or they may be heated extensively and form *fireballs*, or even *detonating bolides*. Tiny magnetic or siliceous spherules and grains are formed by a vaporized meteorite. They are called *micrometeorites*, and can, for example, be found in rain water.

Meteoroids are porous, fragile materials with bulk densities less than one. They are composed of compacted dust and ices (water, ammonia, carbon dioxide). Upon heating, either by the sun or by hitting the upper atmosphere, the meteoroid gives off its frozen gases and is left as a fragile structure, which very easily disintegrates into *micrometeoroids*.

The *visual* or *electromagnetic* phenomena called a *meteor* or shooting star is an accompanying effect of a *meteoritic* particle (resulting from either a meteorite or a meteoroid) being decelerated by the atmosphere. The kinetic energy of the particle is transformed into heat, which partly tends to fuse the particle, partly dissociates and ionizes the air molecules in the shock wave. It is this latter effect we register as a luminous or radar-reflecting trail.

[1] Numbers in parentheses indicate References at end of paper.

Origin

The meteorites are generally believed (2) to be similar in composition to the planetoids. They therefore originate between Mars' and Jupiter's orbits. The only difference from the planetoids is in size. The largest planetoid, Ceres, is 480 miles in diameter. More than a thousand others have been detected, including the yet smallest, Amor, of only a few miles diameter. The meteorites from the planetoid belt form less than 10 per cent of the photographed meteors.

The meteoroids are believed (3) to be of cometary origin. About 90 per cent of the meteor trails are formed by either the meteoroids or by the shattered product, the micrometeoroids.

The periodic meteor showers (see Table 1) are produced by meteoroids, spread out over the elliptic orbit of the mother comet. The earth will in its annual motion intercept the cometary orbits and experience the tenfold larger number of impacts.

Less than one per cent of the meteoritic particles are of interstellar origin. They are distinguished by their parabolic or even hyperbolic velocities.

Table 1 Principal periodic meteor showers

Meteor shower	Date	Comet
Draconids	Jan. 2	.....
Lyrids	April 20	1861-I
Aquarids I	May 6	Halley's
Aquarids II	July 28	.....
Perseids	Aug. 12	Swift's, 1862-III
Orionids	Oct. 20	Halley's
Leonids	Nov. 14	Tempel's, 1866-I

Distribution

The larger particles, the meteorites, are fortunately so scarce that the statistical hazard of impact with a space vehicle becomes negligible. Some 900 meteorites have been recovered on the ground, and were found to range in mass from 10^{-2} grams to 60 tons (2). There is no way of shielding against them.

The meteoritic dust, or specifically the micrometeoroids, presents a severe hazard to a satellite or an interplanetary vehicle. The dust may range in size from 1 to 500 microns (10^{-4} to 0.5 $\times$ 10^{-1} cm). Particles are, however, seldom found below 10 or above 250 microns.

Recently it was found that the density of micrometeoroids was as low as 0.05 g/ccm. They are cindery particles with extreme porosity. By assuming an average velocity of 20 km per sec, the energy range is found to be 10^2 to 3 $\times$ 10^5 ergs for the impacting particles.

The total accretion of interplanetary matter is estimated to be 1000 tons per day for the earth. This corresponds to 20,000 impacting dust particles per square meter per day. It is evident that the study of the impact is of importance.

As a note to the afore-mentioned 1000 tons per day, it should be pointed out that this is an estimate (Fred Whipple), and that other researchers mention 10 tons as the daily accretion. However, I have also seen figures of 10,000 tons per day!

Studies with Vanguard

The IGY satellite program includes experiments to determine the actual intensity of micrometeoroid impact. Basically four methods have been proposed for this study:

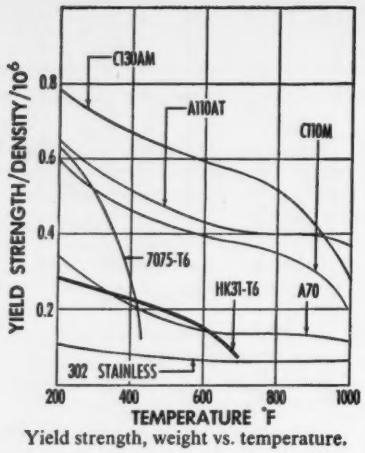
1 Electrically, with Nichrome gages.
2 Sound pickup by microphones.
3 Pressure gages to determine actual penetration.
4 Optical measurements of reflectivity of surface.

Of these we can immediately rule out the latter, which calls for measurements of the reflected sunlight. It is indeed difficult enough just to detect the tiny 20-in. satellite in order to determine its position. A decrease in reflectivity caused by erosion and pitting of the magnesium hull could probably only be detected after a period of several years.

The Nichrome erosion gages consist of a thin ribbon evaporated on a glass plate. The ribbon has a well-defined resistance. Pitting and erosion of the film cause an increase in resistance, which can be encoded to a telemeter signal. This gage will be placed on the skin of the satellite, and probably yield the most reliable information.

A sensitive microphone may pick up the vibrations set in the hull by meteoritic impact. An impact counter together with a recorder will sum up the intensity, and telemeter it to the ground station when passing over it.

The internal pressure of the satellite



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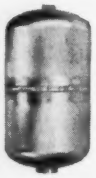

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will be somewhere between zero and one atmosphere. If totally evacuated it will be subject to the external pressure of the atmosphere when on the ground. This calls for a heavier hull construction, and consequently a loss in payload. Also the power package, mercury dry-cell batteries, would need reinforcement to avoid explosion. An internal pressure of one atmosphere would, however, be equally disadvantageous, as this would stress the hull to rupture when in the vacuum of the orbit. The optimal pressure may be of the order of one-third atmosphere.

By equipping the satellite with pressure gages it may be possible to register the eventual pressure loss caused by penetration of the hull by meteoritic dust. It seems, however, that this method cannot yield qualitative results.

Effect on Materials

Impact between particles and space vehicles at very high velocities will transform the kinetic energy of the particle into heat, which tends to fuse the particle and the target. If the target is a very thin plate, a hole will be punched in it. A thicker target will have a hole fused in it. At still greater thicknesses the particle can only fuse a pit, and will not penetrate.

It is of importance to examine the properties of structural materials when subject to impact of high velocity dust particles. The weight factor is critical in space operations, and the minimum thickness of a hull is impenetrable, for micrometeoroids must be found. A meteoritic dust bumper (or shorter, but inaccurately: meteor bumper) has been proposed by Whipple (4), consisting of a thin metal shield surrounding the space vehicle. Upon impact the particle fuses a hole in the bumper, but is simultaneously vaporized itself, and thereby destroyed.

The two basic points to be investigated in the future are thus:

1 The nature of the meteoritic dust: mass, density, composition, energy spectrum.

2 The effect of impact upon structural materials.

Simulating Facilities

The knowledge of the behavior of materials under space conditions is very limited. Test facilities are presently being set up at several research institutes in this country. The first problem is to simulate the extreme energies of the dust particles. A glance at the afore-mentioned energy range (up to 10^{17} ev) shows that electrostatic acceleration of dust particles is out of the question. Magnetic acceleration has some possibilities, even though it seems that stabilization and vacuum problems may prove serious. A modified shock tube has been proposed (5), accelerating monodisperse dust particles with the shock wave.

The materials must be tested over a wide temperature range to simulate space conditions. Besides the structural, optical materials are also of interest, used as lenses for TV cameras, mirrors for telescopes, reflectors for utilization of solar energy.

The next few years will reveal more about the nature of meteoritic dust, about the hazards, and about protection against these ultra-fast particles.

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1 Naugle, J., Private communication, Convair Scientific Research Laboratory, San Diego, Calif.

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4 White, C. S., and Benson, O. O., "Physics and Medicine of the Upper Atmosphere," the University of New Mexico Press, Albuquerque, 1952.

5 "Study of Erosion by High Speed Dust Particles," Research Proposal 57-53 D, Armour Research Foundation.

Operation Moonwatch

OPERATION MOONWATCH is the code name for the visual observing program of Project Vanguard. The director of the Satellite Tracking Program, Fred L. Whipple of the Smithsonian Astrophysical Observatory, has appointed J. Allen Hynek an associate director and Armand N. Spitz a coordinator of visual observations.

While the emphasis is on radio tracking by means of the NRL Minitrack system, Dr. Whipple points out the additional importance of visual tracking of the satellite. These observations will support the early radio tracking, and will probably be the only means of determining the trajectory of the descending satellite, deprived of its limited battery power.

Moonwatch is based on the voluntary support of amateur astronomers all over the world. The International Astronautical Federation, of which the AMERICAN ROCKET SOCIETY is a member, has volunteered its cooperation in establishing observing stations in many countries. Teofilo M. Tabanera, president of the Sociedad Argentina Interplanetaria, Buenos Aires, heads the IAF committee on this project.

The number of observation stations is close to one hundred. Each station will be manned by some twenty observers with binoculars, each of them fixed to cover an arc of 8 to 10 deg of the

meridian. The binoculars or telescopes must at least be of the 7 × 50 type. An attached mirror makes it possible for the observer to sit comfortably in normal position, an important factor, as a period of observation may take several hours.

The satellite is believed to be visible as a sixth or seventh magnitude star, the faintest to be seen by the naked eye. With the telescopes trained on the meridian the observers watch their limited field of the sky. They are required to become familiar with their particular field of vision, so that they can describe and draw the path of the satellite on ready-made star maps with accuracy.

Most important is the exact timing of the satellite. The meridian of the observing station is the line of reference. A timekeeper at the station keeps tuned in to WWV and calls out the seconds when the satellite has been spotted and is about to pass the meridian. The time and position of the satellite is then radioed to a central computing station, which probably will be located in Washington, D. C. Here the orbit of the satellite can be calculated on the basis of three observations, and broadcast to all observing stations.

In this country several public service organizations and private business concerns are contributing to aid the establishment of observing stations.

A group leader is in charge of each observing station, and has the responsibility of selecting good, reliable observers. The stations are training now in order to be ready for the first firings in January 1958.

A "Bulletin for Visual Observers of Satellites" is published by the Coordinator of Visual Satellite Observations, Smithsonian Astrophysical Observatory, 60 Garden St., Cambridge 38, Mass.

Scientific Research in the Soviet Union

(*Continued from page 204*)

in our government and industrial laboratories. I should like to conclude by stating my firm belief that American scientific research still holds a substantial lead and will continue to do so if the American government, industry, and the universities work harmoniously together in strengthening those areas in which we have developed weaknesses, in throwing our full resources into the support of basic research, and in treating the American scientist as a responsible and dedicated person. The minimum that I foresee is that American science will help to preserve the peace and that Soviet scientific achievements, impressive as they may ultimately become, will simply make their just contribution to welfare of the human race.

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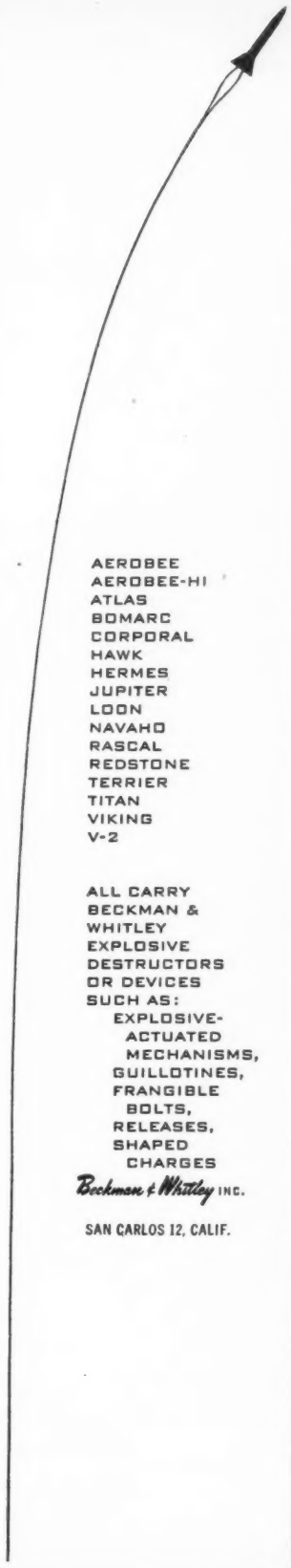

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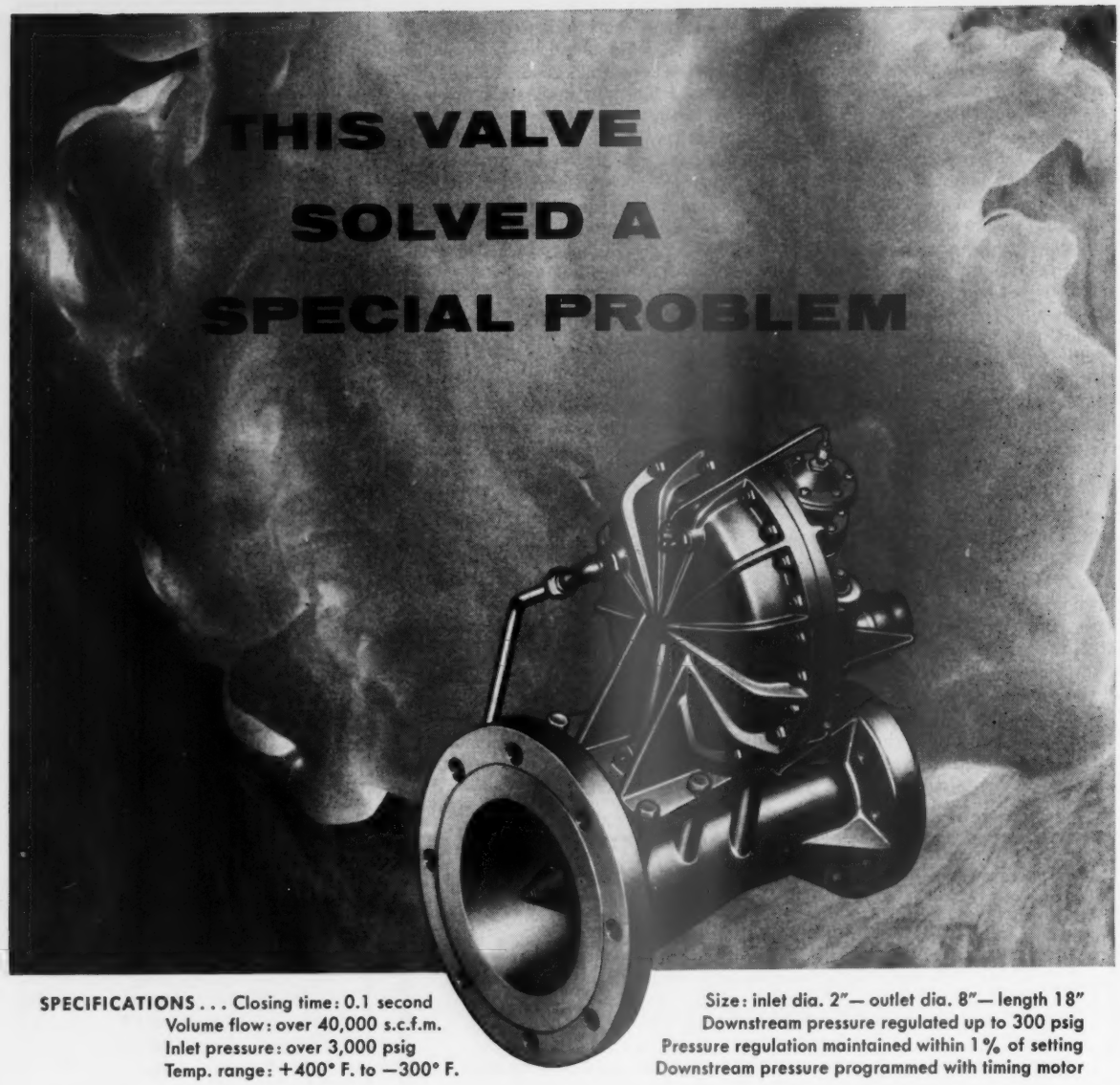

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ARS News

National Capital Section Host to Spring Meeting

A PROGRAM of eight technical sessions—including a two-day symposium on high speed rocket test tracks—and a rocket and satellite exhibit—will be high points of the ARS Spring Meeting scheduled for April 3–6, 1957, at the Sheraton Park Hotel, Washington, D. C.

Other sessions, says Meeting Chairman Andrew G. Haley, will be devoted to propulsive systems, Project Vanguard, and space sociology. Full details will be carried in the March issue of JET PROPULSION, and will be included in the advance program scheduled for mailing later this month.

The 14,000 square foot Sheraton Park Exhibition Hall will house a Rocket and Satellite Exposition during the meeting. First-time displays of missiles, rockets, and Vanguard equipment are expected to be on view, along with data reduction equipment, instrumentation, components, and accessories. For information on the Exposition see page 197.

The meeting, held in cooperation with the National Capital Section, will take place during Cherry Blossom Week in Washington. Chairman Haley and his committee, together with Section President Erik Bergaust, have planned an extensive program of social activities during the Wednesday through Saturday affair. There will be, for example, a meeting-opening "mixer," industry-sponsored breakfasts, luncheons and receptions on each day, and a climaxing Saturday evening banquet which will be addressed by a "major policy-making government spokesman."

A program of ladies activities, now being planned, will be under the direction of Mrs. Erik Bergaust and Mrs. C. Lincoln Jewett.

Other members of the committee are Robert L. Hirsch, William Roennau, William Schundler, Richard Snodgrass, and C. Lincoln Jewett.

The technical program is under the supervision of the national program chairman, Kurt R. Stehling.

Sections

Chicago: On Dec. 12, guest speaker Alfred J. Zaehringer, president of the American Rocket Co., appraised the growing use of solid propellant gas generators. At present a $10–$25 million-a-year business, according to Mr. Zaehringer, gas generators will represent a $100 million-a-year business in about 15 years.

Columbus: Hypersonic research methods was the topic of a talk by John D. Lee, director of Ohio State University's Aerodynamic Research Laboratory, on Dec. 6. At Mach numbers approaching 10 and over, Dr. Lee pointed out, the air supply for a wind tunnel must be heated; otherwise, the air would liquefy as a result of the tremendous expansion through the nozzle.

Afterwards, the group visited the Aerodynamics Laboratory at Don Scott Field, watched a demonstration of a model of a wind tunnel being built for continuous flow of air up to Mach 15.

Holloman: Over 50 people attended the Dec. 11 meeting of the newly formed section. Following social activities, members and guests listened to a lecture and panel discussion of the Holloman Air Development Center Supersonic Test Track.

New Mexico-West Texas: The Judge Advocate General has approved legality of Section's plan to circulate authentic rocket models, pictures, etc., as cereal premiums. With part of the profits they hope to receive from this and other projects, members plan to create college scholarships.

Members elected the following officers for 1957: George L. Meredith, president; G. Harry Stine, vice-president; F. Donald Moore, secretary; Lyle D. Bonney, treasurer.

At the annual meeting on Nov. 8, outgoing president Russell K. Sherburne presented G. Harry Stine an award for his work as editor of *Missile Away*. New Mexico College's Gilbert Moore, guest speaker, described projects Pogo and Hugo.

New York: Under the direction of T. P. Torda, faculty adviser, members of the Polytechnic Institute of Brooklyn Student Chapter are assembling an experimental rocket. Grouped about the unit (above, l to r) are: Thomas Lardner, president; William Peschke, project director; Mario Cardullo; and Dr. Torda.

Selling Science

Over 200 Boy Scouts attended a recent meeting (see Sections) sponsored by the Philadelphia Section, listened to Hugh Winn of General Electric's Missile and Ordnance Systems Dept. talk about the interesting careers in the field of jet propulsion.

More and more ARS groups are sponsoring similar meetings as well as field trips expressly for the younger set in order to interest them in the pursuit of scientific careers. (Seated to Mr. Winn's right is Abe Bernstein, section president.)

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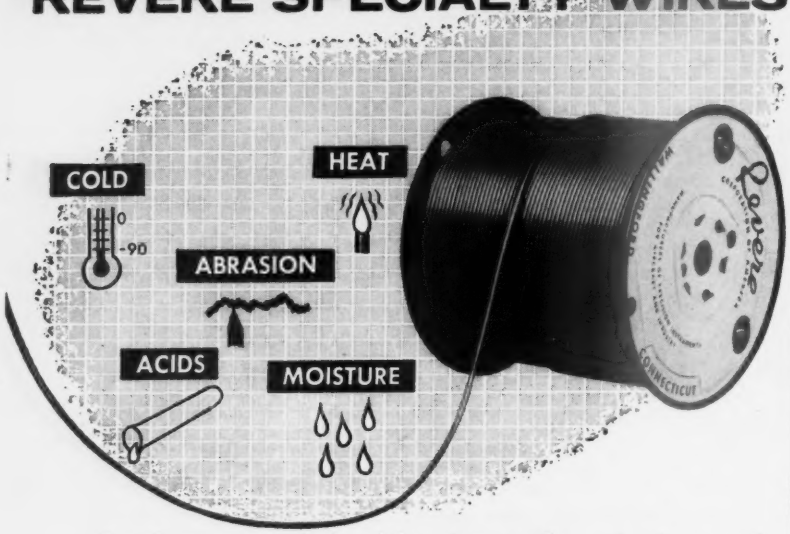

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Philadelphia: As part of its expanding program to interest the younger generation in scientific careers, particularly those in the jet propulsion field, Section recently played host to Boy Scouts on two occasions. Featured speaker at the first meeting on Nov. 23 was Hugh Winn of General Electric's Missile and Ordnance Systems Dept. Approximately 200 scouts between ages of 12 and 16 attended (see picture).

On Dec. 14, 70 scouts (and about 30 adults) listened to I. M. Levitt, director of Philadelphia's Fels Planetarium, talk about Project Vanguard.

ARS Meetings Calendar

April 3–6: ARS Spring Meeting, Sheraton Park Hotel, Washington, D. C.
June 10–13: ARS Semi-Annual Meeting, Hotel St. Francis, San Francisco.
Aug. 25–28: ARS-Northwestern Technological Institute Gas Dynamics Symposium, Northwestern University, Evanston, Ill.
Dec. 2–6: ARS Annual Meeting, New York.

Misfires

GLOSSARY OF MISSILE TERMS AS USED AT PATRICK AFB

Antenna: Uncle Joe's wife.
BC-4: Large dose of headache powder.
Cotar: A tarry substance made out of Co.
Countdown: What happens after a boxer is knocked out.
Dipole: Very sick tadpole.
Data inverter: Electronic engineer who gets things mixed up.
DDM/T: Advanced type of insecticide.
Elsse: The Borden Cow.
Impact area: World's largest hope chest.
LOX: Smoked salmon. Eaten with bagels.
Midop: Personal possive form of *dop:* as in *midop, hisdop, yourdop,* etc.
Minitrack: Very short race course.
Missile: Device similar to skyrocket which goes haywire after being set off.
Photomultiplier: Person who makes double exposures.
Radar Dish: Good-looking girl who operates electronic device.
Recovery: Getting well after a shoot.
Secor: Naval version of Air Corps.
Skid strip: Burlesque on Skid Row.
Sofar bomb: Bomb with very limited range.
Stacked helical: A helical who is well built.
T-time: Five o'clock. One lump or two?

Reprinted from *Missile Away!*, Fall 1956.

B. Ellis (center), head of the Propulsion Department, discusses methods of accurate thrust termination for a ballistic rocket with Dr. Howard M. Kindsvater (left), propulsion staff engineer, and André P. Bignon, propulsion research specialist.

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New Patents

George F. McLaughlin, *Contributor*

Ram jet engine (2,766,581). Harvey W. Welsh, Wycoff, N. J., assignor to Curtiss-Wright Corp.

An expendable ductlike section secured to and extending rearwardly from the main section, and releasable in flight.

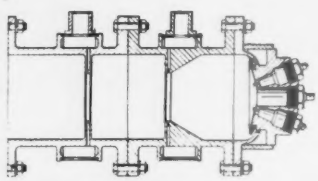
179,348

Airplane design (179,348). Clarence L. Johnson, Encino, Calif., assignor to Lockheed Aircraft Corp.

This design patent applied for in April 1954 covers the configuration originally developed for the U. S. Air Force as a day and night air superiority fighter, and designated the F-104 Starfighter.

Rocket propulsive method (2,774,214). Frank J. Malina and John W. Parsons, Pasadena, Calif., assignors to Aerojet-General Corp.

Thrust is produced by ejecting the gaseous products produced by the combustion of an oxidizer consisting of red and white fuming nitric acids and nitrogen dioxide; and a heterocyclic nitrogen compound of pyrrole and pyridine.



2,774,216

Rocket motors (2,774,216). Sidney Allen, Coventry, England, assignor to Armstrong Siddeley Motors, Ltd.

From a heater at the upstream end of the preheating chamber a small part of the liquid fuel and oxidizer is supplied to spray holes in the wall. The rest of the fuel is fed to a burner at the upstream end of the combustion chamber.

Repeating rocket launcher (2,774,282). Andrew Ballash, Stephen A. Stam, and Paul E. Anderson, Torrence, Calif., assignors to the U. S. Army.

Launching tube including a semicylindrical portion with gas-tight doors to permit loading rockets in a lateral position.

Rocket steering system (2,774,305). Thomas W. Fitzgerald and Robert W. Farren, Williamsville, N. Y., assignors to the U. S. Navy.

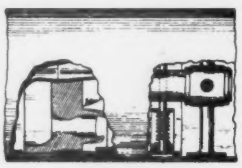
System consists of shifting the center of mass of the vehicle with respect to the vector of propelling thrust, by controlled movement of liquid ballast. Selective transfer of ballast from one compartment to another shifts the center of mass to control the flight direction of the rocket.

Jet flow control for jet-sustained and jet-propelled aircraft (2,774,554). Peter F. Ashwood and George W. Crosse, Andershot, England, assignors to Power Jets (Research and Development) Ltd.

Nozzle unit with a forwardly facing inlet, and a downwardly turned discharge branch, terminating in a nozzle discharging to atmosphere along a line which passes near a transverse line through the C.G. of the airplane. An element in the unit may be positioned to deflect the jet downward or to discharge it rearwardly.

Aircraft with variable wing arrangement (2,774,556). Roger A. Robert, Boulogne-sur-Seine, France.

Jet airplane with two sets of supporting wings disposed in the form of a cross. Wings have different wing loadings and are adapted to support the airplane at high speeds and at relatively low speeds. The fuselage may be rotated about its axis to bring the desired set of wings to a supporting position during flight.



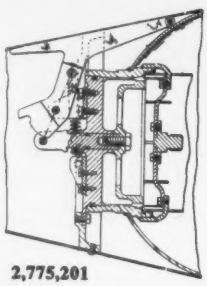
2,775,163

Pre-spin device for rocket launcher (2,775,163). Conrad R. Vegren, Washington, D. C.

Apparatus with canted nozzles which direct the exhaust to propel the rocket and rotate it along its longitudinal axis.

Circular aircraft and control system therefore (2,772,057). John C. Fischer, Jr., San Diego, Calif.

An upper part containing jet propulsion means is rotatably adjustably mounted on the lower part. The upper part may be rotated by the pilot to alter the direction of propulsive thrust.



2,775,201

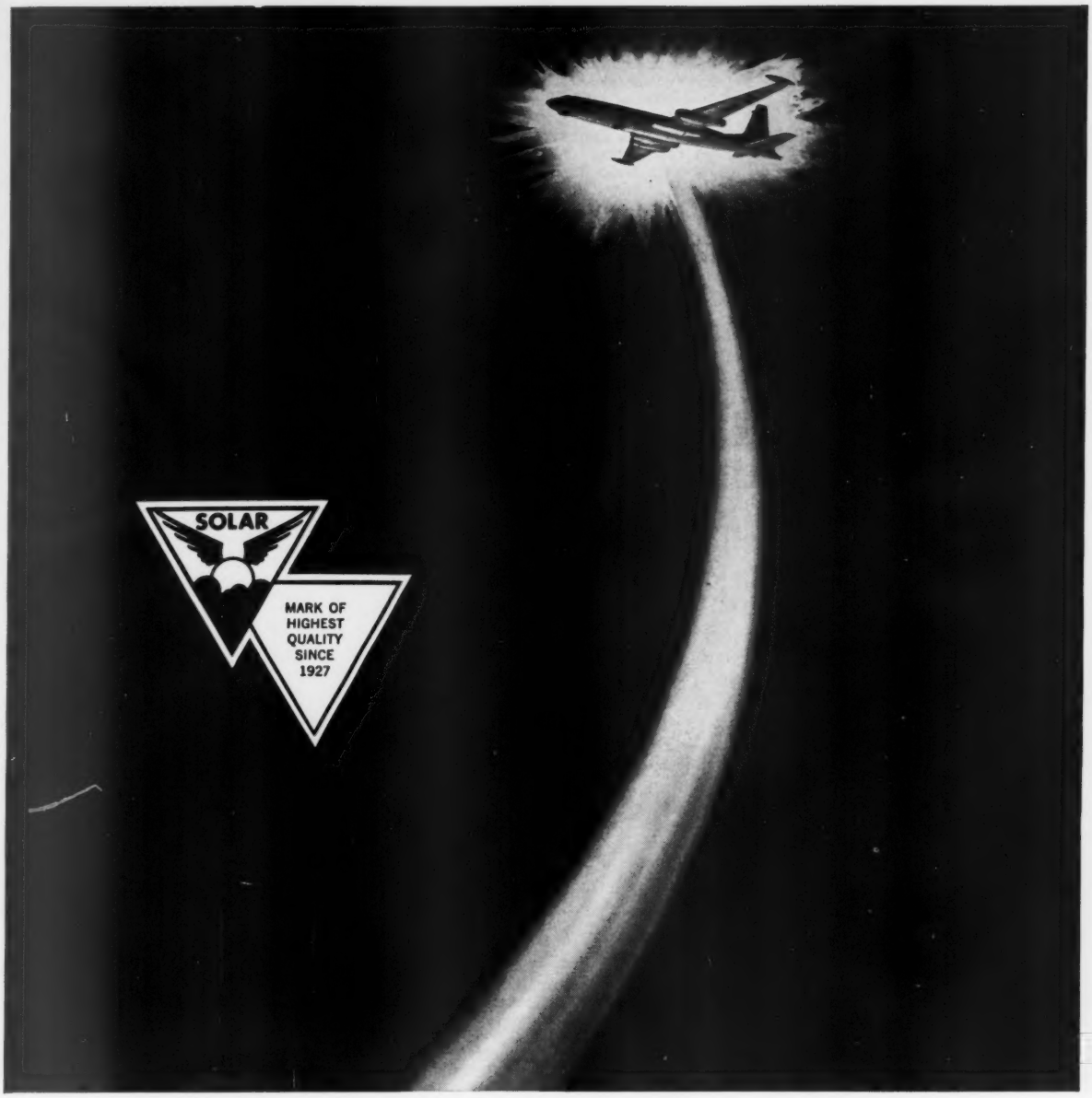
Safety devices for apparatus containing stored pressure energy (2,775,201). Hugh G. Conway, Gloucester, England, assignor to British Messier, Ltd.

In a rocket or other missile, a safety plug adapted to close off the distal end of a pressure release sleeve in the pressure chamber. A spring collet between the sleeve and plug is capable of yielding to permit displacement of the plug.

Infra-red fuel flow controller (2,773,349). Francis G. Bollo and Lucreta M. Whitney, Berkeley, Calif., assignors to Shell Development Co.

Automatic regulation of jet engine fuel flow independent of the amount of air

EDITORS NOTE: Patents listed above were selected from the Official Gazette of the U. S. Patent Office. Printed copies of patents may be obtained from the Commissioner of Patents, Washington 25, D. C., at a cost of 25 cents each; design patents, 10 cents.



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P. A. STURTEVANT CO. ILLINOIS

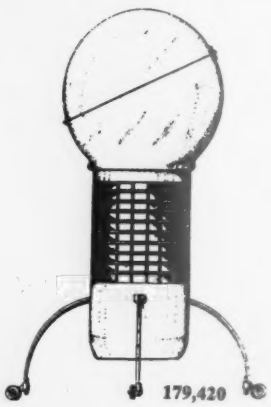
supplied for maintaining fuel-air ratio at a selected value. An infrared analyzer continuously measures the oxidized exhaust gas carbon dioxide content. Fuel flow is varied according to signals from an electronic controller connected to the analyzer.

Combustion chamber assembly for ram jet fuel burner (2,773,350). Hillard E. Barrett, Wm. S. Bower, and Wm. F. Payne, Cedar Grove, N. J., assignors to the U. S. Air Force.

Louvers in a first shroud surrounding a pilot burner are disposed to give the flame a counterclockwise swirl. Main burner nozzles next to a second shroud give the flame from a second set of main burners a clockwise swirl. A third shroud has vanes angled to impart a clockwise swirl to the flame.

Protective wall for use against radiation and explosive forces (2,773,459). Paul S. Sechy, New York, N. Y.

Wall composed of layers of various materials, the inner one of concrete faced on one side by a layer of resilient material. The central layer comprises a group of corrugated sheets connected by horizontal baffles having their inner edges resting against the resilient layer. Outer layers are of heat-resisting material and sheet metal.



179,420

Vertical take-off aircraft or similar article [design] (179,420). Peter G. Kappus, Cincinnati, Ohio, assignor to General Electric Co.

Wingless aircraft for short range flight at moderate speed, has a ball-like upper form and is cylindrical below, supported on the ground by a three-legged landing gear. Gas turbine engine sends hot gases downward. Forward motion is achieved by moving vanes in the jet stream to tilt the vehicle. Mr. Kappus is manager of GE's new product planning development department.

Gyroscopic roll control system for aircraft (2,775,202). Sydney R. Crockett, Inyokern, Calif.

Gyro wheel carried by the control surfaces of a missile is rotated so that precession due to roll will deflect the surface in a direction tending to arrest the roll.

Process for initiating the ignition of rocket fuels (2,775,863). George Traverse, Toulouse, France, assignor to Societe d'Etude de la Propulsion par Reaction.

Method consists of contacting mononitromethane within the combustion chamber, with at least one complex organometallic compound of the formula RMeX, in which R is a lower alkyl radical from methyl and ethyl radicals, Me is aluminum and zinc, and X is at least one halogen from iodine and bromine.

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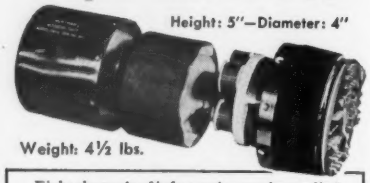
NORTHAM
Miniature Magnetic Tape Recorder



Eight channels of information can be applied simultaneously to a ½-inch tape in the Model MR-1 Recorder (illustrated). This self-contained unit includes transistor timing oscillator and battery power source and operates under axial accelerations up to 500 g. A pre-record carrier system permits direct coupling with D.C. devices such as thermocouples and strain gauge transducers.

MODEL MR-1 SPECIFICATIONS:

Accuracy: . . . . . ±5% full scale
Sensitivity: . . . . 28 millivolts D.C. full scale across 40 ohms impedance
Frequency Bandwidth: . . . . . 0-250 cps
Timing: . . . . . 1000 cps transistor oscillator
Running Time: . . . . . 45 seconds
Applications: . . . . Running time, number of channels and recording characteristics are adaptable to meet requirements of applications—including rocket and aircraft flight testing, oil well logging and atmospheric studies.

WRITE FOR BULLETIN NO. . . . JP-104

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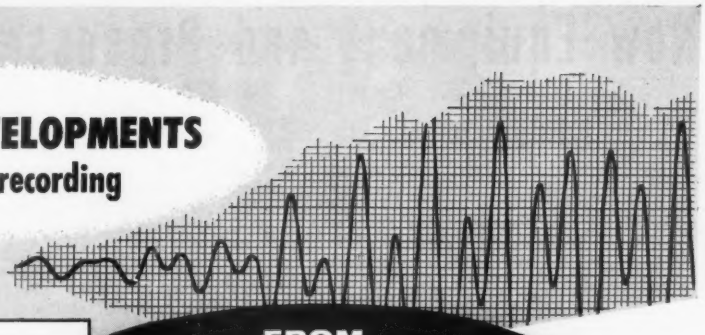
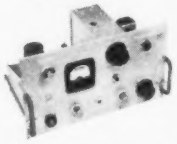
TECHNIQUES and DEVELOPMENTS
in oscillographic recording



FROM
SANBORN

PHASE SENSITIVE DEMODULATOR PREAMPLIFIER PROVIDES A DC VOLTAGE PROPORTIONAL TO AN INPHASE COMPONENT OF AN AC VOLTAGE WITH RESPECT TO A REFERENCE.

THE measurement of the amplitude of an AC voltage component is often necessary in performance studies of servo systems or of suppressed carrier signals over the carrier frequency range from 60 to 10,000 cps. In such cases the demodulator responds to inphase signals and rejects quadrature signals.

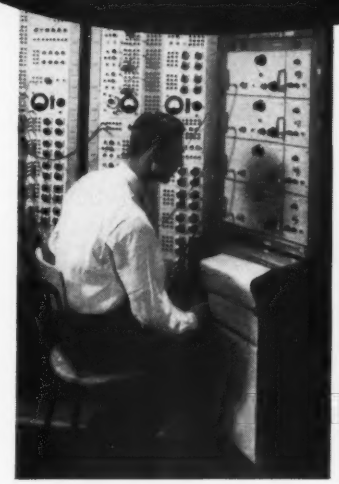


A circuit with these characteristics for use in an oscillographic recording system can be seen in the Model 150-1200 Servo Monitor (Demodulator) Preamplifier. It was developed by Sanborn as one of twelve interchangeable, plug-in front ends for "150" Series equipment, to be used with the appropriate Driver Amplifier-Power unit in any channel of a "150" system. Elements comprising the circuit from input to output, include: compensated stepped attenuator and cathode follower input circuit, phase inverter, push-pull mixer and demodulator stages, differential DC output amplifier and low pass filter. In addition, the chassis contains a VTVM to facilitate accurate adjustment of the reference voltage, and an overload indicator which lights a warning lamp when excessive quadrature voltages exist.

Adaptability to a fairly wide variety of applications is accomplished through broad input voltage, reference voltage and frequency ranges. In order, these are 50 mv to 50 v (for full scale 5 cm deflection), 10 v to 125 v; 60 cps to 10kc. Rise time with low frequency plug-in demodulation filter is 0.1 seconds; with high frequency filter, 0.01 seconds. Quadrature rejection is better than 100.1; for carrier frequencies up to 5000 cycles.

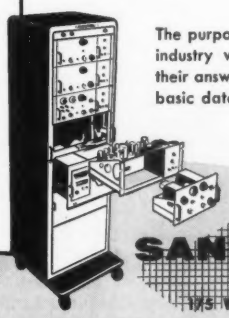
Two representative uses of the Servo Monitor Preamplifier are in the design and adjustment of servo systems, and with instruments used in the design, development or adjustment of other apparatus. The first is illustrated by use of the Preamplifier and associated equipment in the recording of the output shaft amplitude and driving frequency of an AC positional servo; the second by recordings made with a similar setup of the difference between output signals from a gyroscopically-controlled stabilizing device and the "pitch" and "roll" signals generated by a "Scorsby Table" used for testing the device under dynamic conditions.

For a detailed discussion of the principles and design considerations involved in the Servo Monitor Preamplifier, refer to the February, 1955 issue of the Sanborn RIGHT ANGLE, for Dr. Arthur Miller's article on "Measurements with the Servo Monitor Preamplifier."



BASIC FACTORS IN SELECTING OSCILLOGRAPHIC RECORDING EQUIPMENT

WHEN considering any oscillographic system or equipment for your application, three useful "yardsticks" to apply are (1) the recording method, (2) equipment adaptability, and (3) variety of equipment available. Here are the answers to the three, as they apply to Sanborn systems. In the record, rectangular coordinates accurately correlate multiple traces, simplify interpretation and eliminate errors. Permanent traces, produced by a hot ribbon stylus without ink, provide sharp peaks and notches, and clearly reveal all signal changes. One percent linearity results from current feedback driver amplifiers and high torque galvanometers of new design; maximum error is ¼ mm in middle 4 cm of chart, ½ mm across entire chart. From the standpoints of "adaptability" and "variety", Sanborn "150" equipment offers the versatility of 13 different plug-in front ends for any basic system . . . the choice of one- to eight-channel systems . . . the variety of nine chart speeds, timing and coding controls, console or individual unit packaging . . . availability of equipment as either complete systems or individual amplifier or recorder units.



The purpose of the foregoing information is to better acquaint industry with typical oscillographic recording problems and their answers, design considerations in Sanborn equipment, and basic data on what Sanborn makes and how it is being used.

Technical literature and engineering assistance on specific problems are always available from our engineering department.

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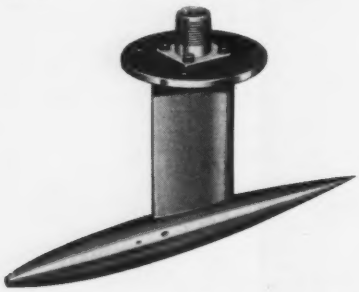
Timing Generator. Weighs 2¼ oz and used in GSAP and Fastair missile camera. Withstands accelerations over 100 g. Provides pulses from 1 to 3000 per sec. Used for making time marks on film. Electromation Co., 116 S. Hollywood Way, Burbank, Calif.

Rugged TV Camera. PD-152 will operate at 15 g and altitudes over 70,000 ft and noise levels up to 175 db. Remote iris and focus adjustment. General Precision Equipment Corp., Pleasantville, N. Y.

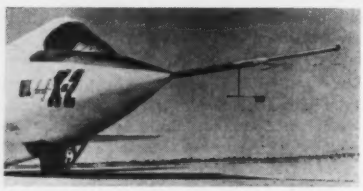


Adiabatic Temperature Probe. Measures airstream stagnation temperatures for aircraft or missiles. Model 49127 has a response time of less than 0.25 sec, a Mach range of 0.3 to 2.0 at altitudes up to 60,000 ft. G. M. Giannini & Co., 918 E. Green St., Pasadena, Calif.

Digital Data Display. Model 756 Digital Indicator permits direct reading of signals from a wide variety of transducers for speed, flow, load, pressure, temperature, or any other variable which is available as electrical signal. Performance Measurements Co., 15301 W. McNichols Rd., Detroit 35, Mich.

Walk-In Test Room. Self-contained for operation of 30–200 F and 20–95% RH. 4′ × 4′ × 7′ to 4′ × 8′ × 7′ high sizes. Hudson Bay Co., Div. of Labline Inc., 3070 W. Grand Ave., Chicago 22, Ill.

New Accelerometer. Measures three mutually perpendicular accelerations simultaneously to 500 g. Response of 25–20,000 cps. Operating range of −65 to 350 F. Weighs less than 1 oz and is about 1 cu in. in size. Gulton Industries, Metuchen, N. J.



Pitot Probe. Static yaw and angle of attack is calibrated for performance through Mach 2.5 and was used by NACA on Bell X-2. Records static and total pressure. Consolidated Avionics Corp., Westbury, L. I., N. Y.

Materials

Silicone Rubber. For hot seals to 600 F. Extruded or calendered. 50 durometer SE-751 parts qualify under AMS 3302 and ASTM TA, BE_1, E_2, F_2, L. Silicone Products Dept., General Electric Co., Waterford, N. Y.

Silicones. Functional organic silanes available in pilot plant quantities. Silicones Div., Union Carbide & Carbon Corp., 30 East 42 St., New York 17, N. Y.

Teflon Glass Fabrics. Pliable below −100 F, inert up to 390 F. Available in single or multiple ply laminates. Shamban Engineering Co., 11617 W. Jefferson Blvd., Culver City, Calif.

Silicon Carbide Cement. Air setting, 30 mesh or finer, has melting point of 2750 F. Water base, applied by hand or spray. Norton Co., Worcester 6, Mass.

Columbium and Tantalum. Oxides and metals to 99.5% purity. Kennametal, Inc., Latrobe, Pa.

Spectra-Strip. Multicolored flat cable, vinyl covered. Wire sizes of 14–30, widths up to 3-in. Organic Development Corp., 8841 Orangewood Ave., Anaheim, Calif.

Missile Kinks

Snark. Reduction in wiring costs on plug-in circuit boards is possible on epoxide-glass fiber, 12-deck, 26-position stepping switch. Wiper contact area is rhodium-plated. Installed in Snark test equipment, the switch is normally sealed in aluminum capsules pressurized with inert nitrogen gas which provides a hermetic seal which still permits access to the switch mechanism for minor adjustments and maintenance. Used in ground support and field test equipment. Northrop Aircraft, Hawthorne, Calif.

Terrier. Compact manifolding for hydraulic interconnecting plumbing lines on Terrier is illustrated in this plastic model. Integral plumbing has 15 ft of lines and operates at three levels. Entire system is tested as a unit. System uses compressed air to deliver power for the missile, wing actuation through integral servo valves and cylinders, and hydraulic power for the remotely located roll actuator. Bendix Pacific Div., 11600 Sherman Way, North Hollywood, Calif.

Product Literature

High Pressure Containers. Fibreglas pneumatic systems are described in this brochure. Manufacturing, specs, and tests are given. Aviation Div., Walter Kidde & Co., Belleville 9, N. J.

Chromalloy. Folder explains process for increasing wear, heat, and corrosion resistance of steel parts by high-temperature diffusion of chromium into surfaces. Chromalloy Corp., 450 Tarrytown Rd., White Plains, N. Y.

Formica. How to choose laminated plastics is given in Technical Catalog no. 4. Formica Co., 4613 Spring Grove Ave., Cincinnati 32, Ohio.

Product Guide. Lists line of fuel regulators and controls. Data on silica gel plugs are also presented. Chandler-Evans, West Hartford 1, Conn.

Thermocouple Assemblies. Catalog 1956 gives specs of thermocouples, pressure sealing glands, explosive valves. Conax Corp., 7811 Sheridan Drive, Buffalo 21, N. Y.

Project Digest. PD-21 describes and gives specs on 3- and 6-channel miniature magnetic-tape recording systems. Cook Electric Co., 2700 Southport Ave., Chicago 14, Ill.

Rocket Consultants. Brochure tells of facilities, personnel, for work on rockets, auxiliary power systems, etc. Fulton-Irgon Corp., Box 764, Bernardsville, N. J.

Precision Ball Bearing. Catalog presents dimensional and series index in addition to visual guides, etc. Barden Corp., Danbury, Conn.

Brazing Alloys. Bulletin 22 has data on four Hi-Temp, high nickel alloys. Handy & Harman, 82 Fulton St., New York 38, N. Y.

Missile Components. General details of rocket fabrication are given in this booklet. Typical operations described. Research Welding & Engineering Co., 10608 Santa Fe Ave., South Gate, Calif.

Inlet Air Diffuser Controls. Discusses controls at speeds of Mach 1.4 and over. Covers spike and ramp or wedge inlet diffusers. Minneapolis-Honeywell Regulator Co., Aeronautical Div., 2600 Ridgway Rd., Minneapolis 13, Minn.

General Catalog. Reviews line of recording oscillographs, processors, amplifiers and power supplies, vibration measuring, pressure pickups, data processing systems, analytical and control instruments. Consolidated Electrodynamics Corp., 300 N. Sierra Madre Villa, Pasadena, Calif.

Drafting Practices. Standard and simplified methods in company use. Public Relations Dept., American Machine & Foundry Co., 261 Madison Ave., New York 16, N. Y.

Press Fittings. Use of Molykote lubricants to eliminate galling, seizing, and distortion. Alpha Molykote Corp., 65 Harvard Ave., Stamford, Conn.

Electronic Research. Four-page brochure tabulates capabilities, contracts in missile and related fields. Servo Corp. of America, 20–20 Jericho Turnpike, L. I., N. Y.

Relief Valves. In-line relief valves are illustrated in Bulletin A5212. Adjustable through 2300–3850 psi. Vickers, Inc., Box 302, Detroit 32, Mich.

Fuming Nitric Acid. Air Force report on rocket propellant is called "Materials for Handling Fuming Nitric Acid With Reference to Thermal Stability," PB 111950, 140 pp., $3.50. Office of Technical Services, U. S. Department of Commerce, Washington, D. C.

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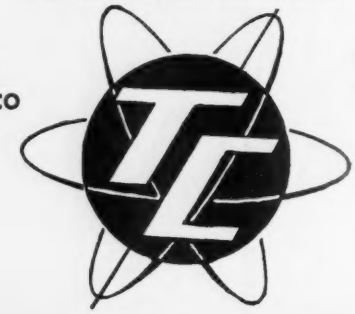

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BASE

100% Peroxide. Bulletin no. 70 gives properties of 90, 95, and 100% hydrogen peroxide. Becco Chemical Div., Station B, Buffalo 7, N. Y.

Synthetic Fluids & Lubricants. Form 6500D has 52 pages and gives properties, applications of polyalkylene-glycol derivatives. Carbide & Carbon Chemicals Co., 30 E. 42 St., New York 17, N. Y.

Radial Draw-Forming. Cold forming of titanium alloy for aircraft, missile use is outlined in this reprint from *Aircraft Production*. Cyril Bath Co., 32430 Aurora Rd., Solon, Ohio.

Cartridge - Actuated Devices. Data sheets give specs on detonator-safe initiators, explosive disconnect, and explosive-driven cutters. Beckman & Whitley, 985 San Carlos Ave., San Carlos, Calif.

Self-Locking Fasteners. Catalog 11-B presents line of Nylock bolts and screws, set screws, hex nuts, threaded inserts, clinch nuts. Nylock Corp., 475 Fifth Avenue, New York 17, N. Y.

Leaded Steel. Booklet SF-2 presents facts for seamless forged and rolling ring applications. ALCO Products, Box 1065, Schenectady, N. Y.

Spraying Ceramics. Details on spray alumina and zirconia in thicknesses from $\frac{1}{2}$ to 25 mil. Metallizing Engineering Co., 1101 Prospect Ave., Westbury, N. Y.

High Temperature Alloy. Hastelloy R-235 properties are given in booklet on vacuum melted, wrought, nickel-base, aluminum and titanium-bearing alloy for service to 1750 F. Haynes Stellite Co., Kokomo, Ind.

Microwave Absorbers. Folder outlines plastics for electronics. Emerson & Cumming, 869 Washington St., Canton, Mass.

Aluminum. 175-page handbook on alloys, forms, etc. Aluminum Corp. of America, 1501 Alcoa Bldg., Pittsburgh 19, Pa.

Transmitter. Four-page Specification 1003-1 describes "Tel-O-Set" for measuring temperature or pressure. Minneapolis-Honeywell Regulator Co., Industrial Div., Wayne & Windrim Ave., Philadelphia 44, Pa.

Research Progress. 54-page progress report for year 1955–1956. Mellon Institute, 440 Fifth Ave., Pittsburgh 13, Pa.

Concentrated Peroxide. Bulletin 77 treats use as propellant. Gives chemical, physical, and ballistic properties. Becco Chemical Div., Station B, Buffalo 7, N. Y.

Rubber to Rockets. 60-page booklet relates story of polysulfides and applications in solid propellant rockets, aircraft, and related fields. Thiokol Chemical Corp., 780 N. Clinton, Trenton 7, N. J.

Hot Rods. Folder highlights industrial use of Crystalon heating elements for electric furnaces and kilns. Norton Co., Worcester 6, Mass.

Silicone Selector. AD 24 E lists major categories of silicones and typical properties. Silicone Products Dept., General Electric Co., Waterford, N. Y.

Strand Burner. Bulletin 4066 outlines four models with pressure ratings of 19,000, 7500, 4000, and 2000 psi. Burning rate measured to 0.01 sec. American Instrument Co., 8030 Georgia Ave., Silver Spring, Md.

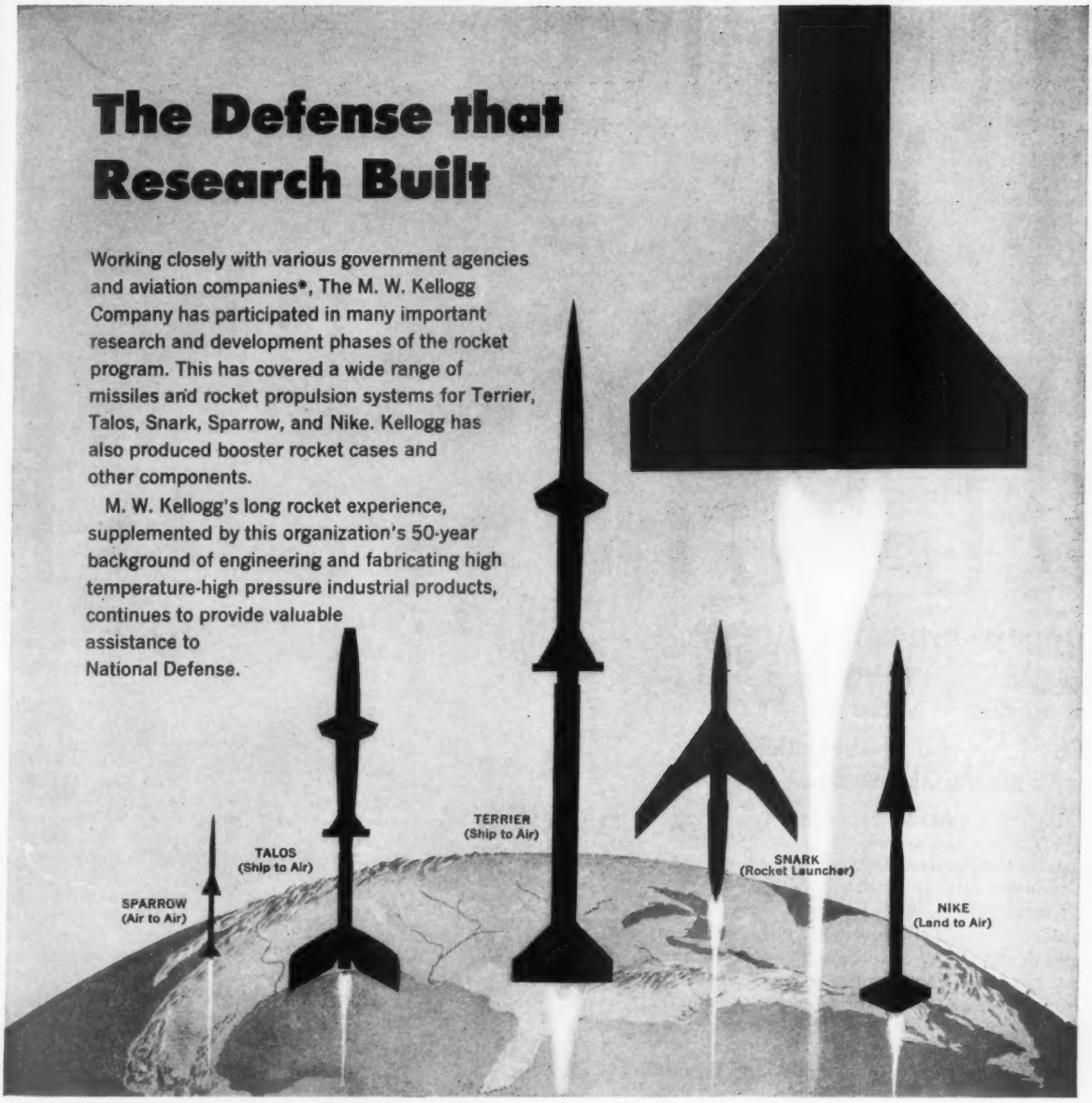
Load Cells. Bulletin gives specs on 6 load cells, plus description of transducer elements. Statham Laboratories, 12401 W. Olympic Blvd., Los Angeles 64, Calif.

Batch Control. Catalog 91–109 describes automatic means for adding fluids to batch processes. Fischer & Porter Co., Hatboro, Pa.

The Defense that Research Built

Working closely with various government agencies and aviation companies*, The M. W. Kellogg Company has participated in many important research and development phases of the rocket program. This has covered a wide range of missiles and rocket propulsion systems for Terrier, Talos, Snark, Sparrow, and Nike. Kellogg has also produced booster rocket cases and other components.

M. W. Kellogg's long rocket experience, supplemented by this organization's 50-year background of engineering and fabricating high temperature-high pressure industrial products, continues to provide valuable assistance to National Defense.



*Including the Navy, Army, Air Force, Allegany Ballistics Laboratory, The Johns Hopkins University Applied Physics Laboratory, and such well-known aviation names as Bell, Boeing, Convair, Douglas, Grumman, Lockheed, McDonnell, Northrop, Republic.

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Book Reviews

Ali Bulent Cambel, Northwestern University, *Associate Editor*

Chemical Engineering Kinetics, by J. M. Smith, McGraw-Hill, New York, 1956, 394 pp. $8.

Reviewed by GEORGE THODOS
Northwestern University

The presentation of this text to the current chemical engineering literature represents the first extensive treatment of chemical reaction kinetics to appear in the last nine years since the introduction of "Chemical Process Principles" by Hougen and Watson. The basic rate relationships defining reaction rates are developed in detail only after the basic thermodynamics involving chemical equilibria at elevated temperatures and pressures are fully discussed.

In this connection, Professor Smith has managed to bring together in an understandable way the roles played by kinetics and thermodynamics, and through the application of a limited amount of experimental data has managed to establish the fundamental rate constants to a number of reactions of current interest. Particular emphasis is placed in the translation of this limited background to the design of reactors operating under different conditions of temperature, pressure, and mode of operation.

The treatment of homogeneous reactions, although concise for the definition of reaction orders in general, is slanted in particular to apply to the kinetic studies involving liquid reactions. Batch and flow systems are treated extensively only after a consideration of the theory of absolute reaction rates and the Arrhenius equation. In addition, semibatch cases are treated, perhaps not so extensively but sufficiently in detail to present an organized pattern of approach to the solution of problems involving this unsteady state condition.

In the treatment of this subject, the parallelism between reaction kinetics and heat transfer is effectively pointed out with the application of these principles to the solution of a number of illustrative problems. For the homogeneous synthesis of carbon disulfide from methane and sulfur, a detailed kinetic evaluation is presented. Stepwise integral reactor calculations are explicitly illustrated and set a good pattern for theoretical developments and integrating concepts.

Although the basic concepts involving rates for catalytic reactions are unchanged, much has been done to bring up to date this very rapidly developing field. The kinetics associated with solid catalytic reactions are comprehensively treated from mass and heat transfer considerations as applied to granular packings. In this connection, the oxidation of sulfur dioxide to sulfur trioxide is extensively investigated and the influence of mass transfer is well explored for this reaction.

The involved subject concerning the influence of mass and heat transfer to catalytic reactors of commercial significance is presented in detail in order to clarify some of the difficulties associated in the steady state flow of heat through reactors where radial effects are significant. The author of this text handles adeptly this difficult subject and permits the establishment of radial temperature profiles through the use of graphical approaches. The introduction of fluidized bed reactors is timely in view of the current commercial significance of such reactors.

Although Professor Smith offers an excellent presentation of this involved field, I believe that some of the recent developments on diffusion coefficients and thermal conductivities of gases as proposed by Hirschfelder would have been worth while to incorporate in the appendix.

Molecular Flow of Gases, by G. N. Patterson; John Wiley and Sons, New York; Chapman and Hall Limited, London, 1956, 227 pp. $9.

Reviewed by HAROLD M. DEGROFF
Purdue University

In the preface to this book, the author states that recent developments in supersonic aerodynamics have brought to the forefront the importance of the molecular viewpoint in the subject of gas dynamics. The apparent intent of the author is to bring together a unified treatment on the molecular flow of gases out of the vast array of current literature.

The author states frankly, "No attempt is made to give a complete treatment of either gas dynamics or the kinetic theory of gases. The essential purpose of this book is to assist the reader in making a transition and outlook from the continuum to the molecular viewpoint." It is the reviewer's opinion that the author has succeeded admirably in his stated objective. Engineers and physici ts, both as students and in the practicing categories, will find that Professor Patterson's book is a useful introduction to the subject.

It should be noted, however, that no claim is expressed for originality. The book represents an excellent compilation of recognized works in the application of kinetic theory of gases to fluid flow. A comprehensive bibliography is appended at the end of each chapter and will serve to link the book to the current literature.

The subject matter of the book is divided into five chapters; however, the context falls into two principal categories. The first two chapters deal with the fundamentals of the simple kinetic theory of gases and their application to isentropic flow; that is, to gas flows in which the molecular motion is describable by a Maxwellian velocity distribution. The remaining three chapters come to grips with matters of more current interest; that is, with the application of the molecular viewpoint to nonisentropic flow which includes boundary layer considerations, shock wave transition, diffuse reflection from solid boundaries, etc.

To be specific, Chapter 1 is a summary of the fundamental equations as derived from the simple kine ic theory in which the molecular model is taken to be a perfect elastic sphere. Using this model, the definition of density and the velocity distribution function are derived. Molecular encounters are discussed and collision frequency is defined. On the basis of this simple model, molecular transport of mass, momentum, and energy is described. The basic ideas of kinetic theory are well elucidated. A few readers may feel that some of the phrases used are a bit cumbersome. For example, the definition of specific density seems to be more drawn out than is required; however, it is this reviewer's opinion that the writer has drawn rather heavily on Jean's kinetic theory of gases, and in attempting to do more than simply paraphrase Jean's theory the author has sacrificed some conciseness and clarity. A slightly more extended discussion of polyatomic molecules in Chapter 1 might have been in order, although this is discussed at more length a little later in the book. For example, in Chapter 1 only two sentences point out the possibilities associated with rotation and vibration of polyatomic molecules, and it is felt that the reader could have been given a little more insight into the coverage to follow later in the book in this connection. Also, the chapter delves only briefly into discussions of equation of state and thermodynamics in general. These subjects are covered more fully later in the book, the only objection here being that the reader would have appreciated a bit of notice to this effect.

Chapter 2 is concerned with isentropic flow and includes sections on the Maxwellian velocity distribution and the corresponding transfer equations. This section again draws heavily on Jean's and is done very well. As a matter of editorial detail, some readers may object to mixing subscript notation and the delta symbol for partial derivatives in the same chapter. The one dimensional expansion wave is treated in Chapter 2 very satisfactorily, except that from a mathematical viewpoint the presentation may be a bit abrupt for the uninitiated reader. The same comment could be applied to the treatment of the expansion wave in two dimensions as set forth in the same chapter. In connection with this, the amount of attention devoted to the expansion wave in a two-dimensional steady flow, and especially to the method of characteristics, seems to be inconsistent with the general tone and purpose of the book.

The basic equations for nonisentropic flow are derived in Chapter 3. The transfer equations are obtained upon the assumption that the distribution of molecular velocities varies only slightly from the Maxwellian law. It is the reviewer's opinion that this is a very pertinent chapter and that it should have received more advanced notice in Chapters 1 and 2. Reference is made to the important work of Enskog, and detailed attention is de-

voted to the methods of Maxwell and Chapman in a very lucid fashion. The point center of force approximation for molecular collisions is introduced in this chapter, and it is shown that this provides a better representation for such thermal properties as the viscosity coefficient than the simple idea of perfectly elastic spheres. The author has drawn upon some of his own contributions in this area with good effect.

The basic equations for nonisentropic flow are applied in Chapter 4 to study such phenomena as diffuse reflection from a solid boundary, shock transition, and the determination of fluid properties. A very good summary of predicted variations of fluid properties with temperature is included as based on the various models of Sutherland, Lennard Jones, and so forth. The application of the point of view of molecular theory of gases to the shock transition problem is particularly well handled. Considerable attention is given in Chapter 4 to the flat plate boundary layer problem, and this is based largely on the work of Chapman and Rubesin. Some readers may take issue with the restriction of the boundary layer discussion to this one principal reference in view of the many other important contributions to the field. However, it should be stated that the molecular description of boundary layer phenomenon ties in very well with the approximations and the points of view adopted by Chapman and Rubesin, and this goes far to explain the author's choice. A review of experimental boundary layer work at high Mach numbers is also included in Chapter 4, and this chapter closes with a section on relaxation effects associated with more complex molecules.

Chapter 5 deals with the mechanics of rarified gases and contains the following sections: discussion of thermal transpiration, transfer of mass, momentum and energy by free molecules, momentum and energy exchange at a surface, drag and heat transfer tests in free-molecule flow, effect of Knudsen numbers on heat transfer, momentum transfer with slip flow, energy transfer with a temperature jump and the transition regime.

The book also contains three appendices: (1) Mathematical aids. This appendix contains some definite integrals and the general velocity distribution function for slightly nonisentropic flow. (2) Differential equations and their characteristics. (3) Summary of the derivation of the basic equations of motion of a gas according to molecular theory–Burnett equations.

The reviewer feels that the author has accomplished his stated purpose with this book; that is, it will serve as an excellent connecting link between the continuum and kinetic theory viewpoint in gas dynamics for all relatively mature readers wishing to make the jump. It will also serve very well to lead the interested into the further study of molecular flow of gases. It is, in general, well written, well edited, and well designed and with the aid of supplementary exercises could conceivably be used as a senior or intermediate graduate level text book in this field.

Engineering in History, Richard Shelton Kirby, Sidney Withington, Arthur Burr Darling, and Frederick Gridley Kilgour, McGraw-Hill, New York, Toronto, London, 1956, 530 + vii pp. $8.50.

Reviewed by R. S. HARTENBERG
Northwestern University

This is an interesting and informative book including, as it does, new material and good illustrations that are not the old standbys. It deals with selected topics of engineering, tracing their development, and in this sense the title is correct. That the authors, in the first line of the preface, call the volume a history of engineering, is unfortunate, for too many things are left untouched and unsaid to justify such a statement. The actual title allows a treatment of selected topics without implying a full consideration of the whole field of engineering. The scope is indicated by the fifteen chapter headings: Origins; Urban Society; Greek Engineering; Imperial Civilization; The Revolution in Power; Foundations for Industry; The Industrial Revolution; Roads, Canals and Bridges; Steam Vessels and Locomotives; Iron and Steel; Electrical Engineering; Modern Transportation; Sanitary and Hydraulic Engineering; Construction; Reflections.

Of the authors, two are engineers (civil and electrical), the third is a historian, and the last a technical librarian. This combination goes a long way toward giving a good coverage of the topics attempted. The continuity does at times

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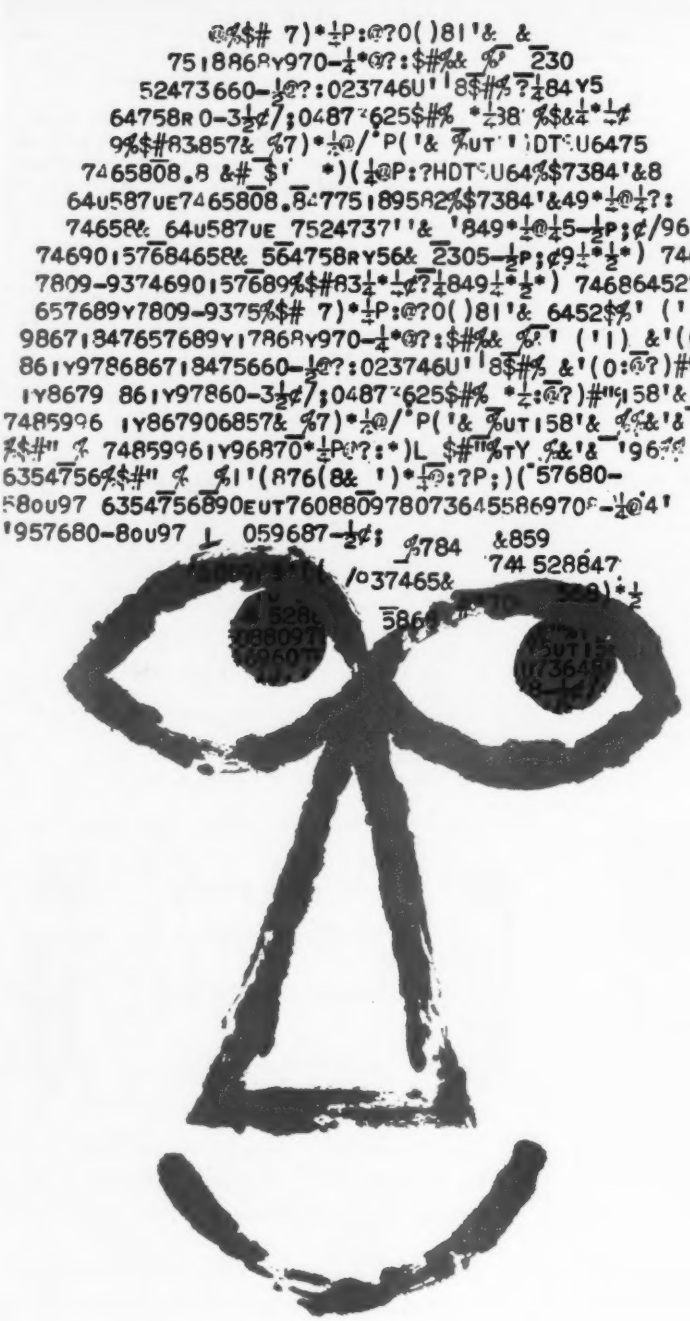

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leave something to be desired, and more reference to the better known events of political history would associate the structure of the engineering past to the general pattern of man's other activities. Occasionally the subject matter meanders, elsewhere it becomes too detailed, and in places it could be tied together better. Thus the data on the Laxey water wheel (page 183) include the $72^1/_2$-ft diameter and 200 hp, but do not mention that it is a pitchback wheel, although in the succeeding paragraph pitchback wheels are remarked on. It might have been noted that this monstrous wheel drove the mine pumps by means of a horizontal, 600-ft-long wooden tension member, supported on what looks like an aqueduct, and that the wheel is still in operation for the tourist trade to gape at (the mines were closed in the depression of the 1930's).

The World of Mathematics, by James R. Newman, Simon and Schuster, New York, 1956, four volumes, 2469 + xvii pp. $20.

Reviewed by R. S. HARTENBERG
Northwestern University

"A small library of the literature of mathematics from A'h-mosé the Scribe to Albert Einstein, presented with commentaries and notes by James R. Newman." So reads the subtitle of this four-volume set of mathematical fact and fancy, of history and philosophy. The material—133 selections—has been ordered with a style and comprehension that gives the reader, even the nonprofessional, a greater appreciation of mathematics than he would think possible. One does not need to be a mathematician to enjoy and profit from these volumes. The pace is necessarily uneven, varying from easy to pretty rough. There is fare for everyone to savor; even if the understanding is not complete, the flavor is delightful. Enthusiasm and joy run through each volume; each may be read for sheer exuberance and not as a duty.

The commentaries and notes—there are a substantial number—form a valuable part of the text, for they introduce authors and ideas. The biographical essays present not only the personality of the man, but, more importantly, show him in the setting of his time and give a view of the particulars under which he flourished; one gets, from the interplay of concepts and historical circumstances, not only a feeling for the past, but also a sense of belonging to the community.

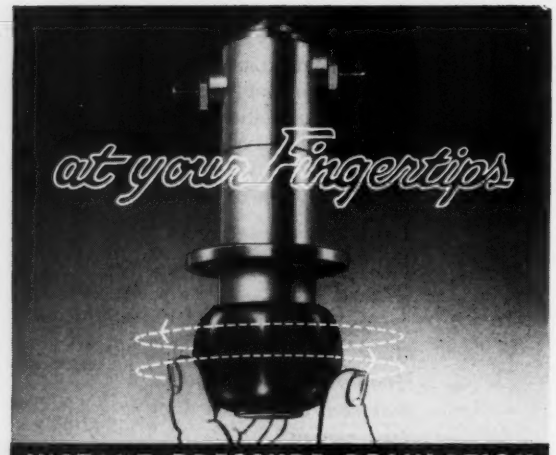
So many books on the history of mathematics are available that it is but natural to question the need of this set. The story of the past has often been put up as a series of dull accountings that seemingly touched only the long dead. Here, however, is a lively, fascinating chronicle in which the evolution of thought, of discovery, of experience and practice are presented, not only by the original authors but sometimes even more succinctly by the editor's commentaries that weave the separate strands into a whole cloth. After all, even an enthusiast cannot hope to read all the detailed and too numerous articles and books: in this set, important features are arranged in an enlightening and stimulating manner. The bewildering array of ideas—a heterogeneous mass to most of us—is built into a framework of thought by lucid connections that shape the mass into something meaningful and endowed with a unique beauty.

Mathematics, it is seen, is more than our ordinary association with it ever led us to suspect. It ranges into the fields of music, aesthetics, social sciences, ethics, biomechanics, games (how to play tennis or golf!), not to mention insurance and the more obvious forms of engineering applications. Among the latter the laws of similitude are seen to indicate the size limits of various animal species. But it is impossible to detail the many wonders that are to be found.

Mr. Newman, one of America's foremost authorities on the literature of mathematics, is by academic birth a lawyer. As member of the board of editors of *Scientific American,* sometime consultant on the literature of mathematics to the Library of Congress and Chief Intelligence Officer of the United States Embassy in London, author or co-author of several books, his is a well-qualified background for the fifteen-year task that yielded the engaging story of the science that allowed all other sciences to prosper.

Book Notice

Formulas for Stress and Strain, by R. J. Roark, McGraw-Hill, New York, 1954, 381 pp. $7.50. This is the third edition of this well-known book.



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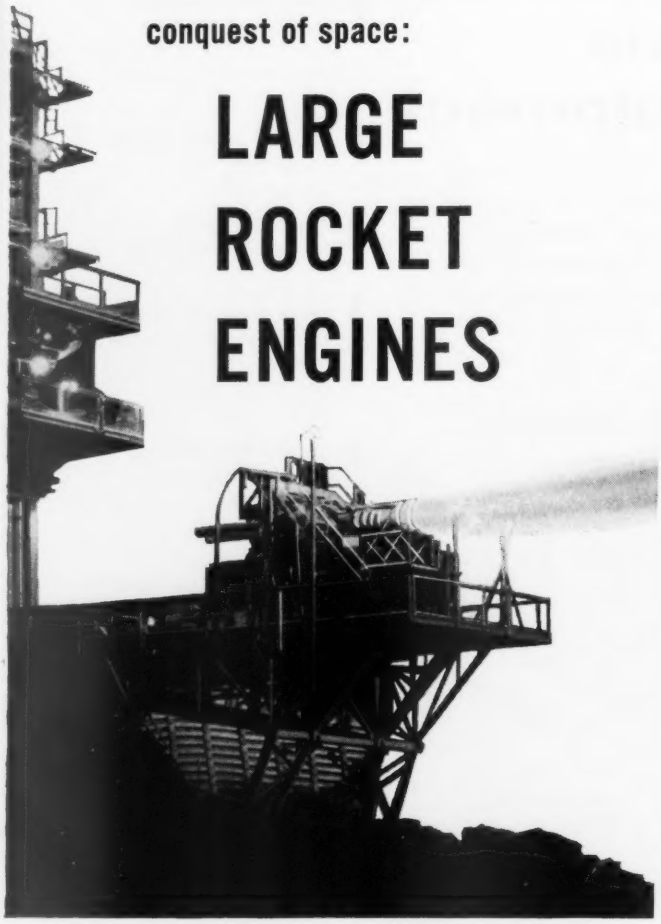

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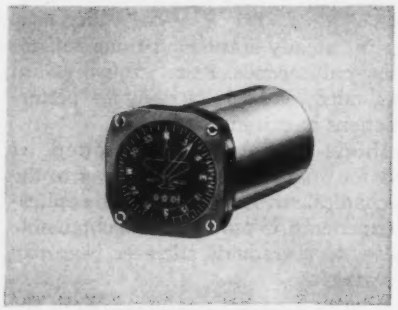

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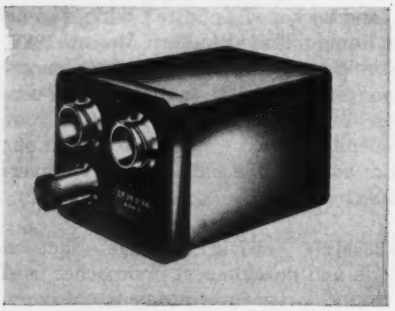

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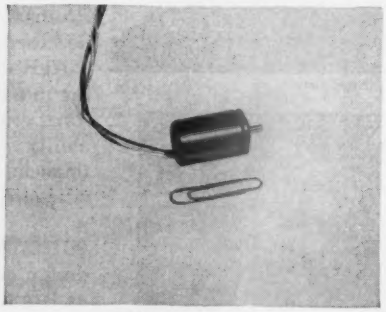

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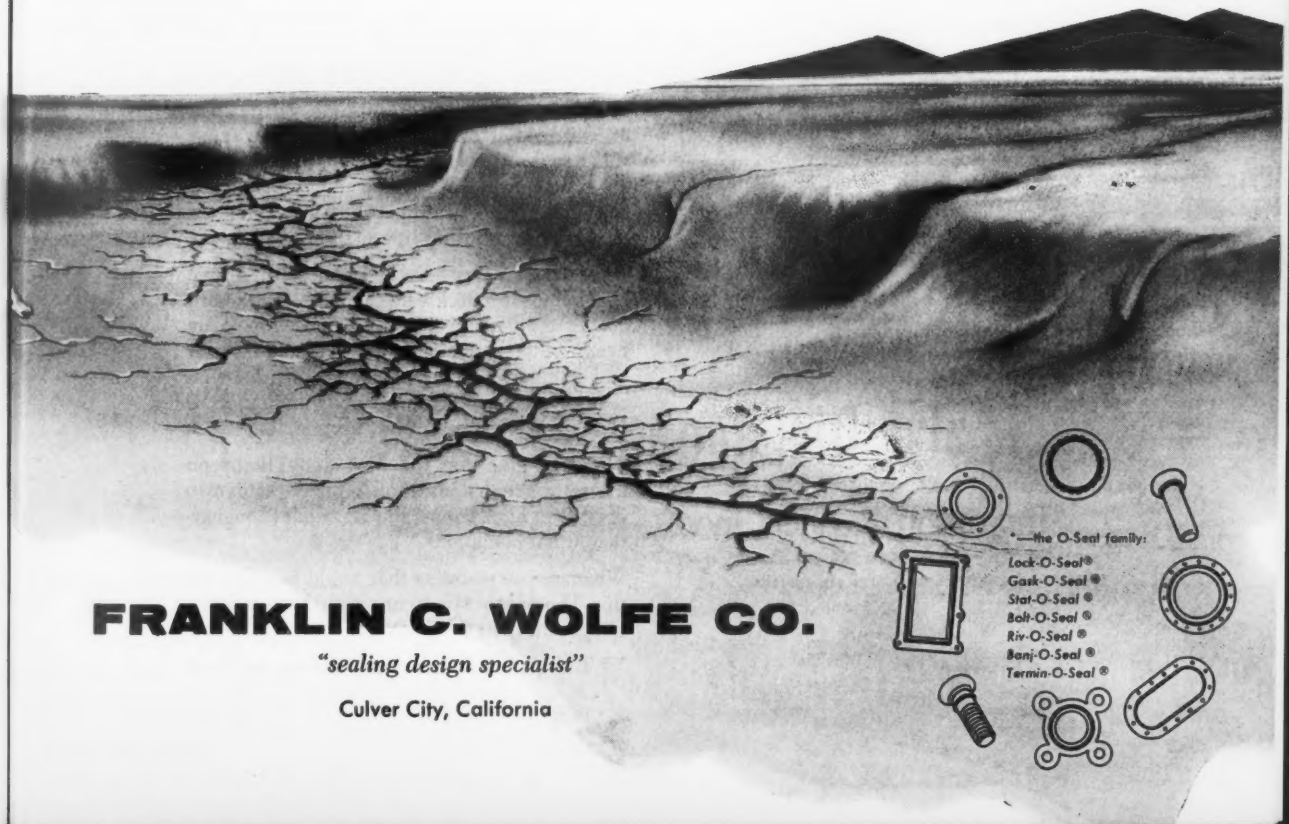

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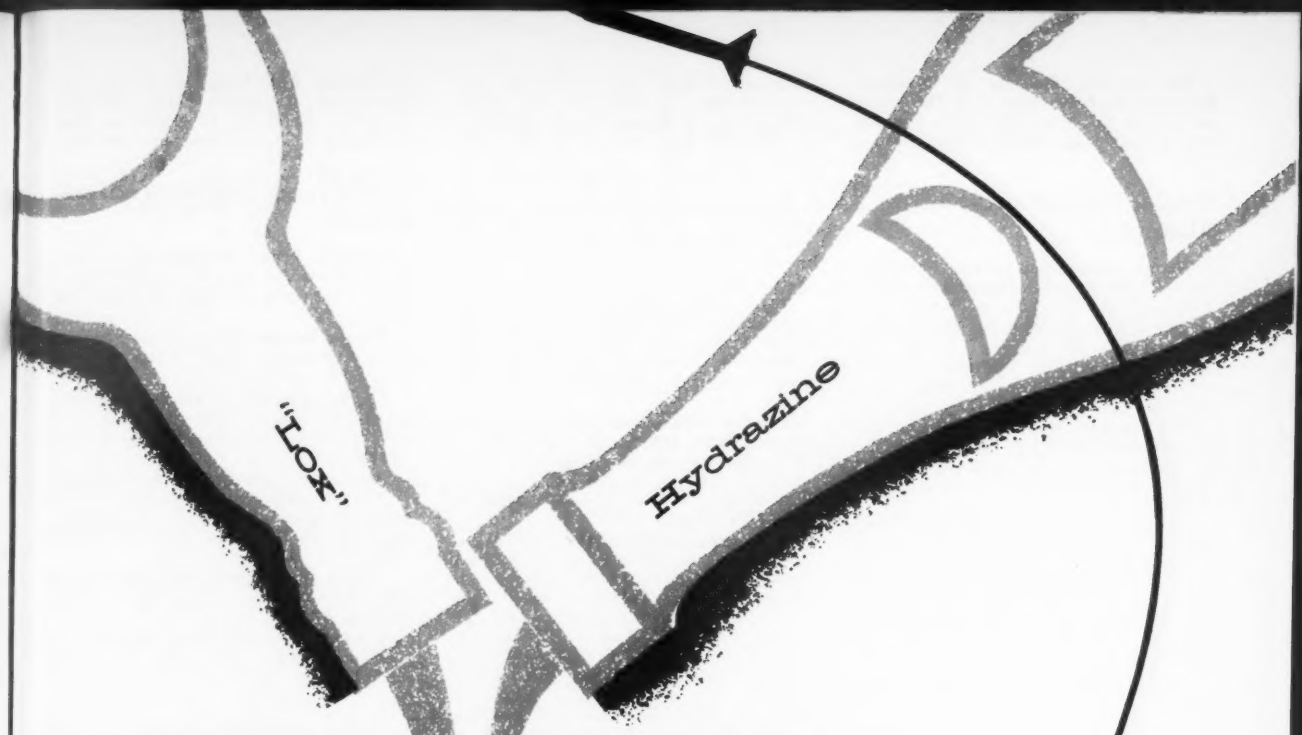

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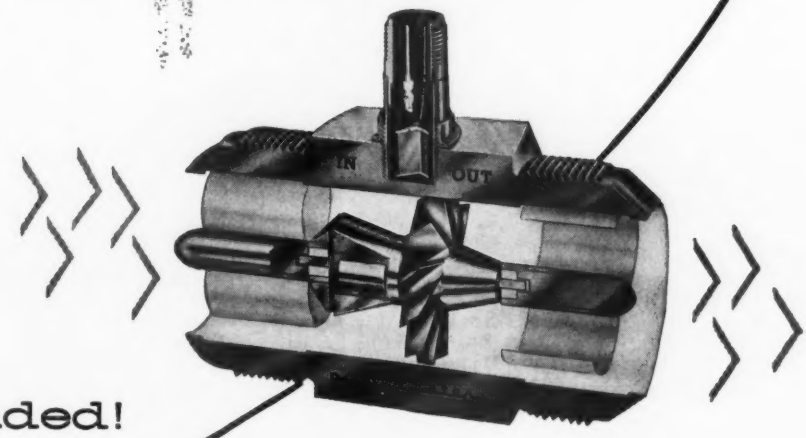

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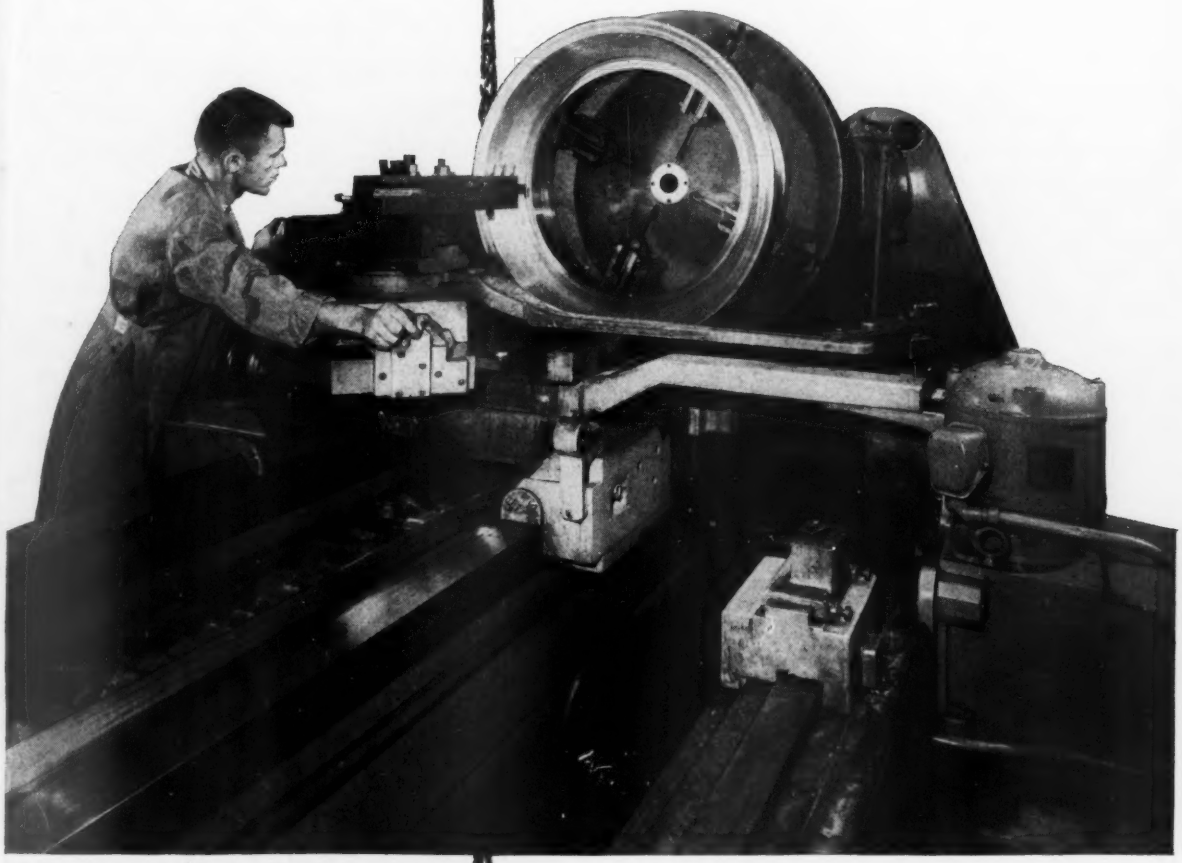

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BOEING AIRPLANE COMPANY 109
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GENERAL ELECTRIC COMPANY (Aircraft Nuclear Propulsion Dept.) 209, 214
Deutsch & Shea, Inc., New York, N. Y.

GENERAL ELECTRIC COMPANY (Missile & Ordnance Systems Dept.) 194
Deutsch & Shea, Inc., New York, N. Y.

GENERAL MILLS, Mechanical Division 205
Knox Reeves Advertising, Inc., Minneapolis, Minn.

GENISCO INCORPORATED 206
Clyde D. Graham Advertising, Los Angeles, Calif.

GRAND CENTRAL ROCKET COMPANY 120
Byron H. Brown and Staff, Inc., Beverly Hills, Calif.

GULTON INDUSTRIES, INC. 233
Conti Advertising Agency, Inc., Ridgewood, N. J.

HAYDON, THE A. W. COMPANY 196
Cory Snow, Inc., Boston, Mass.

HEILAND DIVISION, Minneapolis-Honeywell 121–124
Tool and Armstrong Advertising, Denver, Colo.

INTERNATIONAL BUSINESS MACHINES CORPORATION 112, 113
Benton & Bowles, Inc., New York, N. Y.

KELLOGG, THE M. W. COMPANY 221
Fuller & Smith & Ross Inc., New York, N. Y.

LAVEZZI MACHINE WORKS 204
R. W. Sayre Co., Chicago, Ill.

LOCKHEED AIRCRAFT CORPORATION
MISSILE SYSTEMS DIVISION 213
Hal Stebbins Inc., Los Angeles, Calif.

THE MARTIN COMPANY 185
Vansant, Dugdale & Company, Baltimore, Md.

MCCORMICK SELPH ASSOCIATES 198
Gerth-Pacific Advertising Agency, San Francisco, Calif.

MCDONNELL AIRCRAFT CORPORATION 224

METALLIZING ENGINEERING CO., INC. 182
The Schuyler Hopper Co., New York, N. Y.

MISSILE DEVELOPMENT DIVISION, North American Aviation, Inc. 239
Batten, Barton, Drustine & Osborn, Inc., Los Angeles, Calif.

NEWBROOK MACHINE CORPORATION 219

NEW DEPARTURE, A Division of General Motors Corporation 189
D. P. Brother & Company, Detroit, Mich.

NORTH AMERICAN INSTRUMENTS, INC. 216
Heintz & Co., Inc., Los Angeles, Calif.

NORTON COMPANY 114
James Thomas Chirurg Company, Boston, Mass.

PACIFIC VALVES, INC. 188
Harold H. Larsen Advertising, Long Beach, Calif.

PHILLIPS PETROLEUM COMPANY 240
Lambert & Feasley, Inc., New York, N. Y.

POTTER AERONAUTICAL COMPANY 235
Richard & Gunther, New York, N. Y.

RADIO CORPOPATION OF AMERICA 111
Al Paul Lefton Company, Inc., Philadelphia, Pa.

THE RAMO-WOOLDRIDGE CORPORATION 202
The McCarty Company, Los Angeles, Calif.

REACTION MOTORS, INC. ..... Second Cover
Doyle Kitchen & McCormick, New York, N. Y.

REEVES INSTRUMENT CORPORATION 195
Robotham & Peck, Incorporated, Hartford, Conn.

REPUBLIC AVIATION CORPORATION 191
Deutsch & Shea, Inc., New York, N. Y.

RESISTOFLEX CORPORATION 192
Marsteller, Rickard, Gebhardt and Reed, Inc., New York, N. Y.

REVERE CORPORATION OF AMERICA 212
W. L. Towne Advertising, New York, N. Y.

ROBBINS AVIATION 226

ROBERTSHAW-FULTON CONTROLS COMPANY 115
Riley-Nelson Company, San Diego, Calif.

ROCKETDYNE, A Division of North American Aviation, Inc. 229
Batten, Barton, Durstine and Osborn, Inc., Los Angeles, Calif.

SANBORN COMPANY 217
Culver Advertising, Inc., Boston, Mass.

SANDIA CORPORATION 222
Ward Hicks Advertising, Albuquerque, N. Mex.

SOLAR AIRCRAFT COMPANY 215
The Phillips-Ramsey Co., San Diego, Calif.

SOUTHWEST PRODUCTS CO 224
O. K. Fagan Advertising Agency, Los Angeles, Calif.

STATHAM LABORATORIES 184
Western Advertising Agency, Inc., Los Angeles, Calif.

P. A. STURTEVANT CO. 216
Ross Llewellyn Inc., Chicago, Ill.

TELECOMPUTING CORPORATION 220

THOMPSON PRODUCTS, INC., VALVE DIVISION 232
Meldrum & Fewsmith, Inc., Cleveland, Ohio

TICKLE, ARTHUR, ENGINEERING WORKS, INC. 204
Ritter Sanford & Price, Inc., New York, N. Y.

TITANIUM METALS CORPORATION OF AMERICA 106
W. L. Towne Advertising, New York, N. Y.

WESTVACO CHLOR-ALKALI DIVISION, FOOD MACHINERY AND CHEMICAL CORP. 110
James J. McMahon Incorporated, New York, N. Y.

WIGGINS, E. B., OIL TOOL COMPANY, INC. 105
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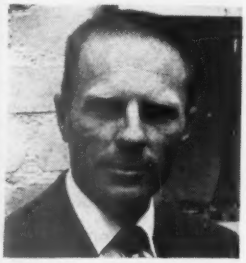
Accept this challenge and you can travel faster and farther than you ever thought possible on one of the most important programs in the free world today—North American's complete weapons system responsibility for the Air Force SM-64 Navaho Intercontinental Strategic Guided Missile.

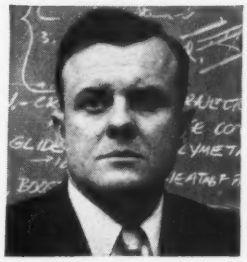


DOUGLAS K. BAILEY received his BS degree from the University of California. He joined North American ten years ago as a senior design engineer. Today he is chief, Missile Design Section—responsible for missile design engineering and analysis. Doug and his family live in Long Beach where he participates in golf, bowling and sports car activities. He is currently organizing road races in Southern California for the Long Beach MG Club.

Unprecedented programs have been completed and more are to come. Others are being developed, modified and perfected as we enter another exciting phase following a successful flight test program at Patrick Air Force Base using a test vehicle known as the X-10.

The fascinating nature of this work has already attracted the world's best informed missile men. Top-tier men have opportunities in almost every field of engineering—including some of the most advanced work being done today in aerodynamics, thermodynamics, high temperature materials and aero-elasticity.

Solving these problems is bringing forth new formulae and new production techniques. One example is Chem Mill, the process of shaping metals—including titanium and newest alloys—to previously unattainable designs by chemical etching. This method reduces weight ... increases strength. The idea came from a North American Missile engineer.



Navy vet **GEORGE W. JEFFS** earned both his BSAE and MSAE from the University of Washington. About 9 years ago he started his professional career with North American as a junior aerodynamics engineer. Now, 5 promotions later, this 30-year old veteran of missile work is chief, Advanced Design Section. He lives in Downey, California with his wife and 3 children. His hobbies include fresh-water fishing and hunting for quail and pheasant.

This is the kind of opportunity open to you. You can share our knowledge and add to it.

Recent graduate engineers can step into established groups. Experienced men will find even greater opportunities in the new groups that are being formed. And you'll do this in a management climate that stimulates personal growth and rewards it with responsibility, professional recognition and material benefits. Further, you can continue your studies with the aid of North American's Educational Refund Plan ... live and work in Southern California ... in near-ideal climate.

Let us know what kind of creative engineering interests you. (Please include highlights of your education and experience.)

Write today to: Mr. R. L. Cunningham, Engineering Personnel Manager, Dept. 2-JP.
Missile Development Division, 12214 Lakewood Blvd., Downey, California.

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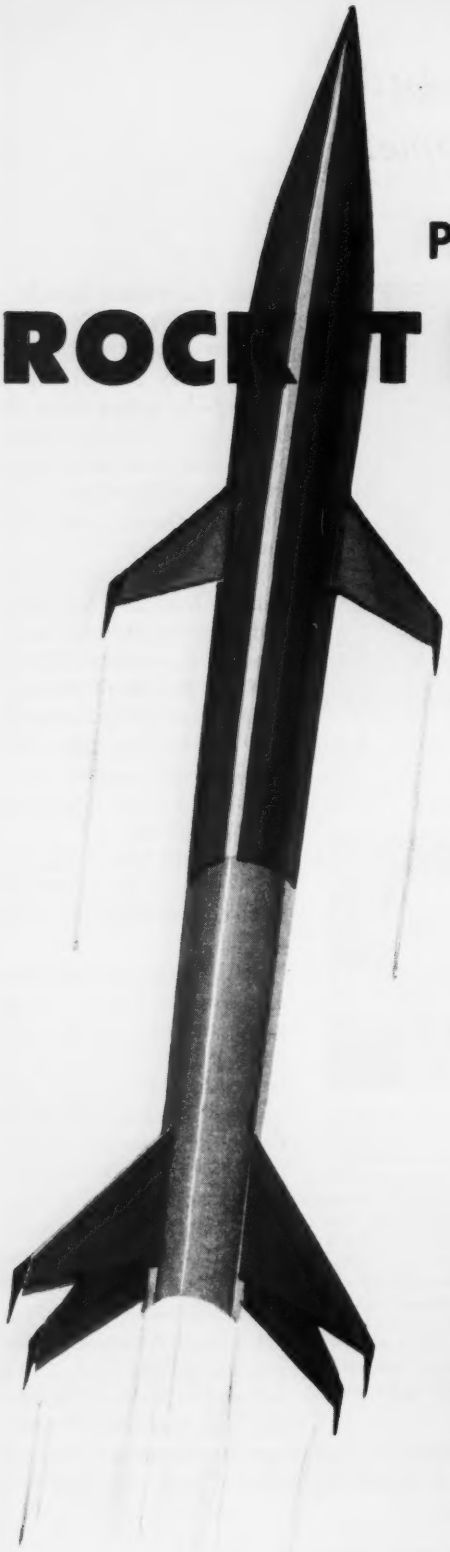

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ROCKET PROPULSION

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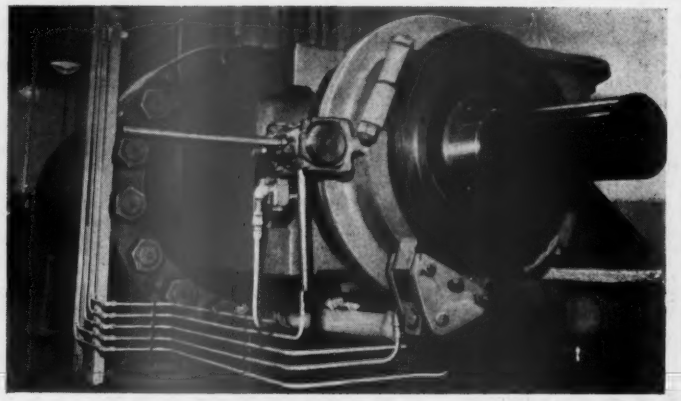

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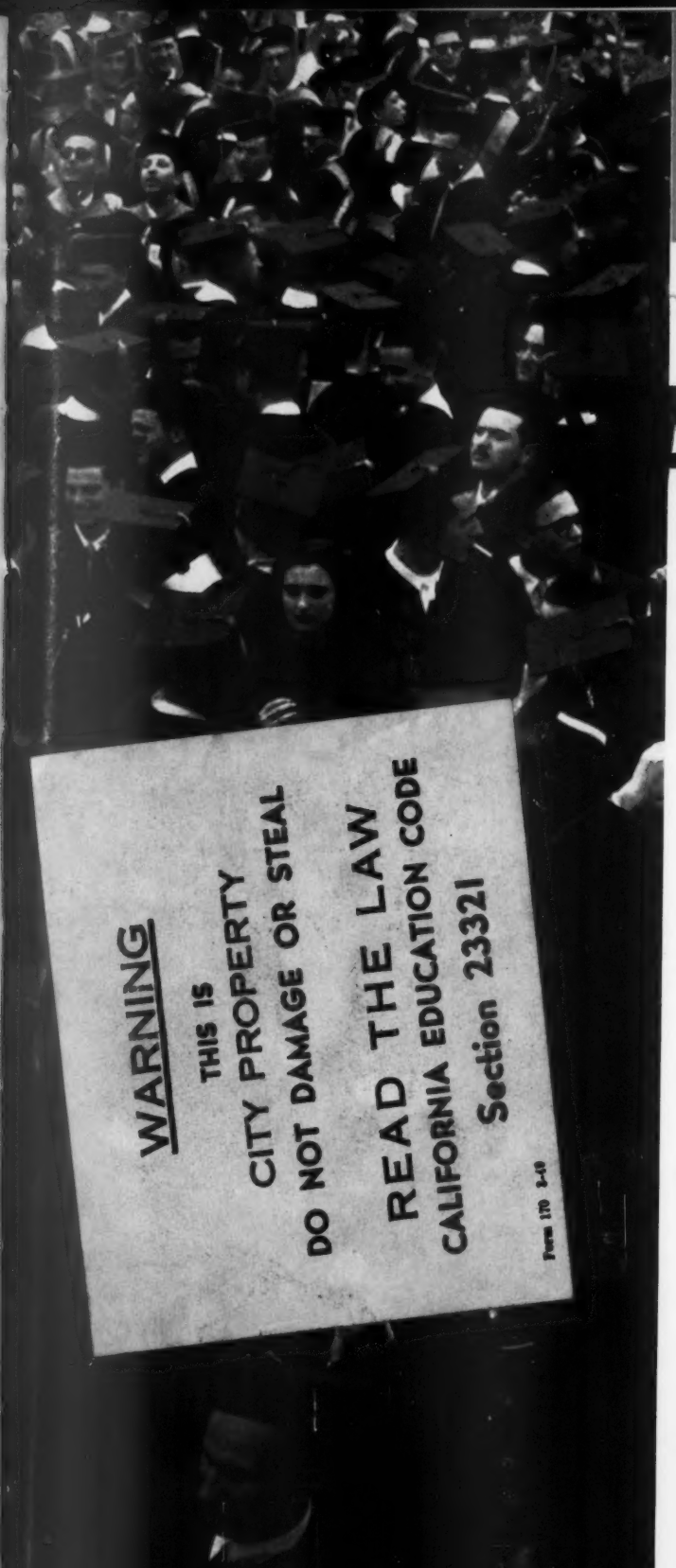


JET PROPULSION

Journal of the
AMERICAN ROCKET SOCIETY

Rocketry — Jet Propulsion Sciences . . . Astronautics

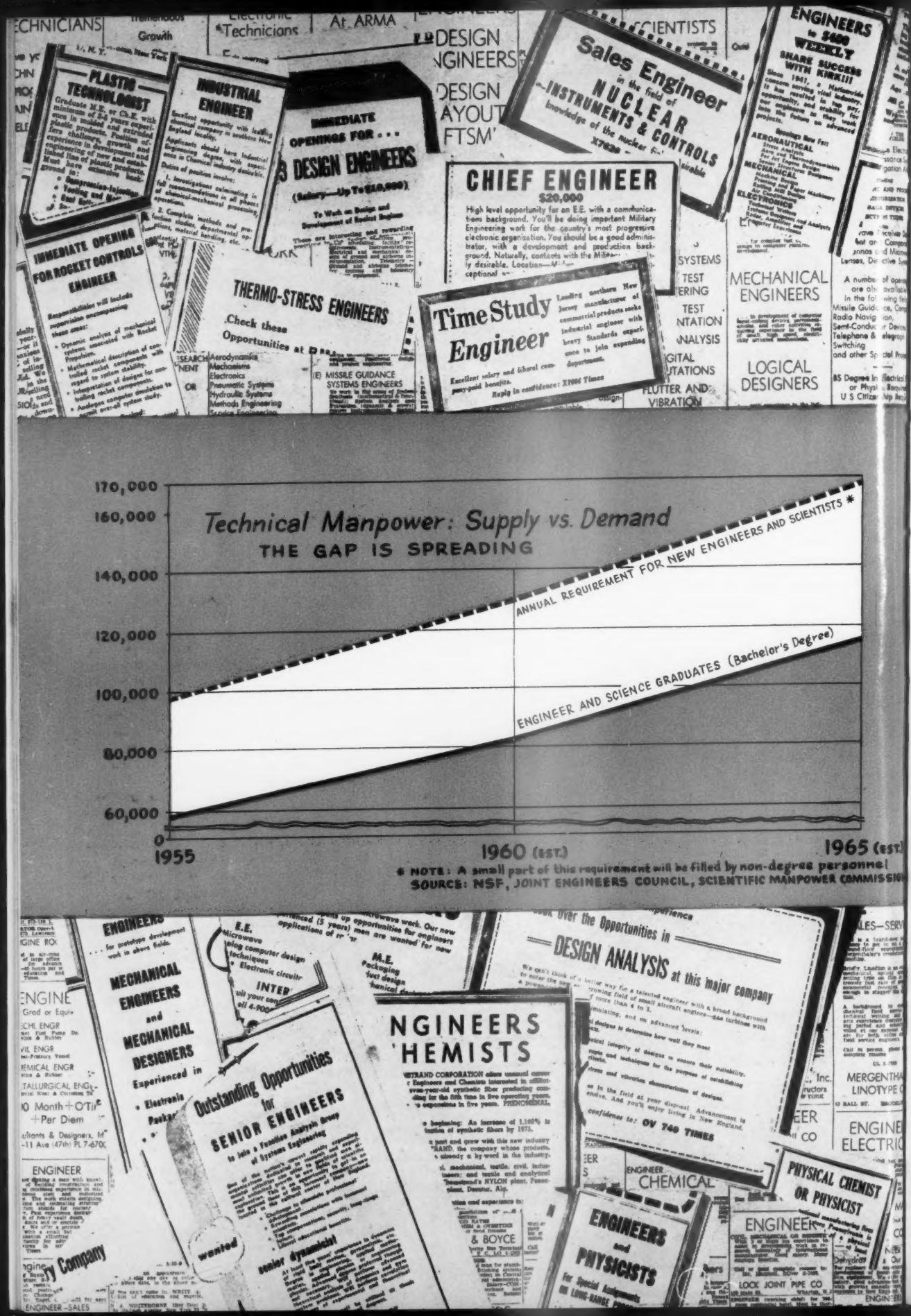
VOL. 27 FEBRUARY 1957 NO. 2, PART 2
(In Two Parts)

SCIENCE AND TECHNOLOGY

STACKS CAREERS IN THE ROCKET AND GUIDED MISSILE INDUSTRY

STACKS

Aerojet-General Corp.	4-S
Aircraft Gas Turbine Division General Electric Co.	6-S
Applied Physics Laboratory The Johns Hopkins University	8-S
Arma Division of American Bosch Arma Corp.	9-S
Atlantic Research Corp.	10-S
Battelle Institute	11-S
Beech Aircraft Corp.	12-S
Bell Aircraft Corp., Weapons Systems Division	14-S
Bendix Products Division Guided Missile Section	13-S
Bulova Research and Development Laboratories, Inc.	16-S
California Institute of Technology Jet Propulsion Laboratory	17-S
Chrysler Corp.—Missile Operations	18-S
Convair-Astronautics Division of General Dynamics Corp.	19-S
Cornell Aeronautical Laboratory, Inc.	22-S
Douglas Missiles Engineering Department Douglas Aircraft Co., Inc.	20-S
Fairchild Engine Division Fairchild Engine and Airplane Corp.	23-S
Firestone Tire and Rubber Co. Guided Missile Division	26-S
Ford Instrument Co., Division of Sperry Rand Corp.	24-S
Grand Central Rocket Co.	27-S
The Martin Co.	28-S
McDonnell Aircraft Corp., Missile Engineering Division	29-S
Olin Mathieson Chemical Corp., Explosives Division	30-S
Pan American World Airways, Inc.	31-S
Phillips Petroleum Co.	32-S
The Ramo-Wooldridge Corp.	33-S
Raytheon Manufacturing Co.	34-S
Reaction Motors, Inc.	35-S
Rocketdyne, A Division of North American Aviation, Inc.	36-S
Rohm & Haas Co. Redston Arsenal Research Division	37-S
Systems Laboratories Corp.	38-S
Thiokol Chemical Corp.	39-S
Thompson Products, Inc., Accessories Division	40-S
United Aircraft Corp., Hamilton Standard Division	41-S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INDUSTRIAL ENGINEER
IMMEDIATE OPENINGS FOR . . .
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Sales Engineer
in the field of
NUCLEAR
INSTRUMENTS & CONTROLS
CHIEF ENGINEER
$20,000
ENGINEERS to $400 WEEKLY
IMMEDIATE OPENING FOR ROCKET CONTROLS ENGINEER
THERMO-STRESS ENGINEERS
Check these Opportunities at Dee
Time Study Engineer
MECHANICAL ENGINEERS
LOGICAL DESIGNERS
Technical Manpower: Supply vs. Demand
THE GAP IS SPREADING
ANNUAL REQUIREMENT FOR NEW ENGINEERS AND SCIENTISTS *
ENGINEER AND SCIENCE GRADUATES (Bachelor's Degree)
170,000
160,000
140,000
120,000
100,000
80,000
60,000
0
1955
1960 (EST.)
1965 (EST.)
* NOTE: A small part of this requirement will be filled by non-degree personnel
SOURCE: NSF, JOINT ENGINEERS COUNCIL, SCIENTIFIC MANPOWER COMMISSION
ENGINEERS
MECHANICAL ENGINEERS and MECHANICAL DESIGNERS
Experienced in
Outstanding Opportunities for SENIOR ENGINEERS
DESIGN ANALYSIS at this major company
ENGINEERS CHEMISTS
PHYSICAL CHEMIST OR PHYSICIST
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CAREERS IN THE ROCKET AND GUIDED MISSILE INDUSTRY
JET PROPULSION, FEBRUARY 1957, PART 2

To Our Readers . . .

The purpose of this editorial is twofold. First, it is to reaffirm and document the serious shortage of scientists and engineers in this country. Then, with the rest of the supplement, it will, we hope, serve to alleviate this shortage.

In addition to our 7000 paid subscribers, composed principally of engineers and scientists now working in the jet propulsion field, this special issue will go to 15,000 college-caliber high school and prep school students and to 15,000 college and university students currently enrolled in science and engineering courses.

To the college and university students, particularly those who are about to graduate, this Supplement should serve as a guidepost to the particular career opportunity for which each individual is best fitted and in which he will be most content.

For the pre-college student, we hope that this careers issue generates sufficient excitement and enthusiasm to point him in our direction—or at least toward a career in science or engineering.

And those among our regular readers who may not be serving this field as efficiently as they might will, perhaps, be able to find on the following pages positions which will better utilize their valuable talents.

At the same time, the editors take the position that each company has a similar obligation to make the most efficient use of skilled personnel already on its staff.

EDITORIAL

How to Fill an Infinite Void

A GREAT deal has been said and written about the growing shortage of engineers and scientists in the United States. Most authorities agree that there is a shortage and that it is fast becoming critical. The problem now is what caused it and, more important, what can be done about it.

Last year, U. S. schools graduated an estimated 63,000 science students. Approximately 26,000 of these were engineers.

Compared to 1955 figures, this indicates an over-all gain of 4000 science graduates. Engineers showed the largest gain, accounted for approximately 3400 of the 4000; chemists showed an increase of 500; physicists, of about 100. Mathematics graduates just about held their own.

Indications are that the 1957 crop of science graduates will show somewhat greater gains. But encouraging as these rises may seem, they are grossly inadequate. They are not enough to fill present demands, nor sufficient to bridge the gap between projected curves of demand and supply.

Where Does It Hurt? According to estimates by the Engineers' Joint Council and the U. S. Bureau of Labor Statistics, this country *now* needs a minimum of 40,000 engineering graduates a year. The U. S. Office of Education doesn't expect us to reach this *current minimum* until 1963.

And the shortage of scientists, now about 20,000, is expected to reach 50,000 by 1960. Who's feeling these shortages:

• Education: A recent survey by the National Education Association showed that of 277 universities, state colleges, and large private colleges, about one-third were unable to fill important positions in engineering while three-fourths had vacancies on their physical science staffs. Currently, there is a deficit of 140,000 qualified teachers in the U. S., according to Rear Admiral Hyman Rickover, USN.

• Industry: A National Science Foundation survey covering 200 companies found that at least one-half of the companies were unable to hire enough research scientists and engineers to fill their requirements. One out of three reported major shortages of such personnel. Among those hardest hit in this respect is the aircraft industry. Some companies reportedly have turned down government research projects as a result of this shortage.

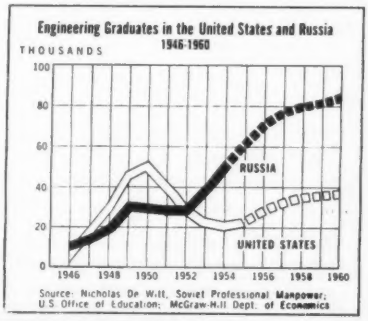
• Government: Employing over 20 per cent of all active engineers and scientists, the government has, if an easier time than education, then at least a harder time than industry hanging on to its scientific personnel principally because of comparatively lower pay scales. In a typical month, for example, the over-all government employee accession rate was 1.5 per 100 employees but the separation rate for the same period was 1.9. And at the government's vital National Advisory Committee for Aeronautics, for the same period, the accession rate was 1.7 while the separation rate was 1.9.

Time on Russia's Side: More significant, perhaps, than any individual shortage is the total picture which Assistant Defense Secretary Donald Quarles terms "potentially, a greater threat to national security than any aggressor weapons known."

According to the McGraw-Hill Department of Economics, we are *now* on a par with the Soviets in technical manpower, but the trend (see chart) is against us.

In 1955, Soviet schools graduated 126,000 science students, of which 59,000 were engineers. The U. S. total was 59,000, of which 22,589 were engineers. McGraw-Hill projections for the five-year period 1956–1960 peg U. S. engineering output at 153,000 against at least 400,000 for Russia with an additional 150,000 for satellites and Red China.

In Russia, 30 per cent of the college



Published by the American Rocket Society, 500 Fifth Ave., New York 36, N. Y.

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students are in engineering against 8 per cent in the U. S. Another 30 per cent are in natural sciences. Moreover, unlike the U. S., the Soviet is ploughing a large proportion of science graduates back into teaching. This means an even more rapid buildup in the future.

According to Allen Dulles, director of the Central Intelligence Agency, in the 10 years ending 1960, Soviet Russia will have graduated 1,200,000 scientists and engineers compared to 900,000 for the U. S. Moreover, because of Russia's greater population and its lower average age, the Soviet will still have a greater untapped manpower reserve than this country.

And all available evidence indicates that the new Russian graduates are for the most part just as good as ours!

What Happened? Before probing possible solutions to this technical manpower shortage, it might be worth while examining some of the causes.

Most significant, perhaps, has been the changing complexion of U. S. labor requirements. In 1940, about one in 148 workers was a scientist or engineer; the figure today is about 1 in 80. Thus, while the over-all labor demand is rising rapidly, the need for technically trained people is curving upwards at an even faster clip, and becoming steeper with each new advance in automation.

Contributing to this, of course, has been the almost phenomenal development of such fields as atomic energy, aircraft, guided missiles, and electronics within only the last decade or so. Where there were fewer than 90,000 engineers and scientists engaged in research and development 15 years ago, there are now over 200,000.

As a rather pointed example of this steeply rising R&D demand, the McGraw-Hill Department of Economics cites the development of a typical fighter plane: In 1940, it required 17,000 engineering manhours; today, it takes 1.4 million; and in 1960, it will require over 2 million.

And, from George A. Roberts, vice-president of Vanadium-Alloys Steel Company: "Jet engines, missiles and satellites cannot be advanced without better materials." And while 500 metallurgical engineers are being graduated annually, says Dr. Roberts, industry needs at least twice that many in each of the next five years to develop these materials.

There are, of course, many other factors that contributed to this shortage. Principally:

- Not enough has been done to attract students to careers in science and engineering.
- Little effort has been made to make more effective use of the limited technical people now available.
- There are now about 1 million fewer students of college age than there were in 1940—a legacy of the depression and its low birth rate.
- A survey made by the U. S. Bureau of Labor Statistics in 1949 discouraged many from entering engineering and other technical fields. The survey concluded, at the time, "the shortages of trained men will (likely) be alleviated in a few years."
- Financial reasons and lack of interest combine to keep an estimated 160,000-200,000 high school students from even entering college.
- Perhaps as many as 15,000 science and engineering graduates are committed to active duty with the military each year.
- Few colleges have programs specifically designed for students in the newer fields, such as nuclear or missile engineering, in which the need is most critical.

Which Way Out? The next and, perhaps, most important question is: "What can be done about this critical shortage of technically trained people?"

First, of course, it is obvious that we cannot nor will not adopt an educational policy like that of the Soviet in which the benefit of the individual is regarded as secondary to that of the state.

As a matter of fact, it is reported that leading U. S. educators, already showing signs of uneasiness because of the pressures being brought to bear on top students to turn them toward science and engineering careers, are beginning to make a strong plea for "the well-rounded man" and "a return to normalcy." Recently, for example, in defense of the humanities, Arthur S. Adams, president of the American Council on Education (and former Dean of Engineering at the Colorado School of Mines), asked, "Why do we have to follow in the footsteps of the Soviet Union?"

We do not have to, nor are we following in Russia's footsteps. But just to make sure we don't get stepped on and to maintain our present rate of economic and technological development, we must do something about the shortage of trained technical personnel.

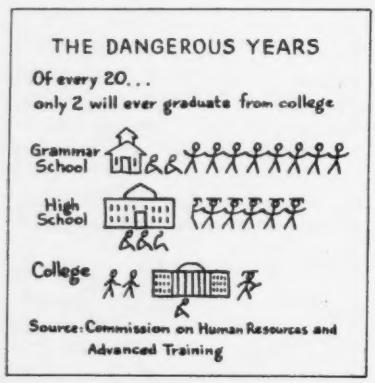
From among the many possible solutions to the problem—some already suggested or actually underway—those listed merit mention or, as the case may be, re-iteration (see: To Relieve the Technical Manpower Shortage). They seem to us a sound approach to the problem and, if adopted by those concerned, the best solution to the present shortage obtainable under prevailing circumstances. In addition, we believe, their adoption will set a sound pattern for the future, assure an adequate supply of scientists and engineers for peaceful growth as well as "cold war" contingencies.

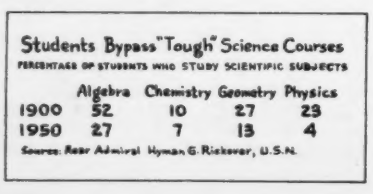
Our Role: At the same time, as a technical society, ARS is vitally concerned with the shortage. As part of the rapidly growing jet propulsion field, we are even more concerned with solutions. Our responsibility only begins with the foregoing review.

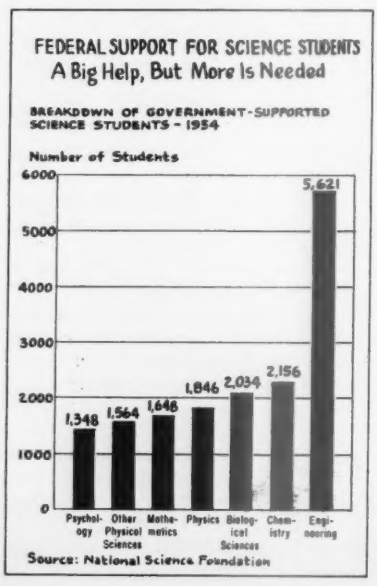
Both as a society and as individuals we must take an active part in relieving this critical shortage of scientists and engineers—not only in our own field, but in all technical areas.

We have already made some significant beginnings. As witness:

- This, our second Careers Supplement, will reach over 30,000 students (who have expressed an interest in receiving it), a gain of more than 20,000




Students Bypass "Tough" Science Courses
PERCENTAGE OF STUDENTS WHO STUDY SCIENTIFIC SUBJECTS
Algebra Chemistry Geometry Physics
1900 52 10 27 23
1950 27 7 13 4
Source: Rear Admiral Hyman G. Rickover, U.S.N.



over last year's initial special issue. Designed to show students the full and and varied fare offered by careers in science and engineering, this is, perhaps, our most important contribution.

• Distribution of the Supplement, as last year, will be carried out by faculty members, many of whom are ARS members, all of whom are very much aware of the technical manpower shortage. In addition to insuring highly effective distribution of the supplement this will add an important personal touch, enable the faculty members to give the students individual guidance.

• Following up a request from headquarters, ARS Sections are establishing local education committees (see JET PROPULSION, Jan., p. 73). At this time, their function is to interest high school and junior high school students in scientific careers through lectures, field trips, etc.

It is hoped that committee members will be able to work closely with student counselors, will establish themselves as "supplemental" science advisors easily available to all interested students. Among other things, the committees will be able to sort out and keep track of those students with a technical bent, encourage them to go to college, help them prepare to meet admissions requirements, advise them in the selection of colleges and curriculum, and help those who need it obtain financial assistance.

• Last year, the AMERICAN ROCKET SOCIETY established its first financial award for students, the $1000 ARS-Chrysler Award. The SOCIETY plans to expand this student award program as fast as proves feasible. In addition, the New Mexico-West Texas Section recently set up its own local science scholarship program; eventually, other ARS Sections will be able to do the same.

• On an individual or group basis, ARS members are fostering an interest in science among youngsters through sponsorship of Science Explorer Posts in conjunction with Boy Scouts of America (see JET PROPULSION, Nov. 1956, p. 1014).

• On a national basis, the SOCIETY has established student chapters at a number of colleges and universities to further interest in the jet propulsion field. Initiated in late 1955, this program expanded rapidly last year, is expected to maintain the pace through and beyond 1957.

But, as we said, this is only a beginning. These efforts must be sustained, expanded, and new efforts must constantly be made to alleviate this dangerous and growing shortage of scientists and engineers.

More youngsters must be directed into the sciences and engineering. Available technical talent should be taken advantage of to the fullest extent, not hoarded or misdirected. We must interest more students in the field of jet propulsion particularly, show graduates where they best and most efficiently fit in this field.

Though we may bring the problem up again as a reminder occasionally, the time has come for words to give way to deeds.

THE EDITORS

ACKNOWLEDGMENTS: "The Shortage of Scientists and Engineers," McGraw-Hill Dept. of Economics; "The Growing Shortage of Scientists and Engineers—Proceedings of the Sixth Thomas Alva Edison Foundation Institute," New York University Press; "Trends in the Employment and Training of Scientists and Engineers," "Soviet Professional Manpower," NSF-156 and NSF-157, National Science Foundation; EMC-SMC Newsletters #96 and #99, Engineering Manpower Commission and Scientific Manpower Commission; Atomic Energy Commission.

To Relieve the Technical Manpower Shortage

EDUCATORS SHOULD:

✦ Improve high school teaching techniques particularly in mathematics and the sciences.

✦ Make more efficient use of existing facilities at college level and above.

✦ Raise teachers' salaries to a par with those of industry.

✦ Receive greater financial support for science and engineering students from industry, government, and technical associations.

✦ Use retired scientists and engineers to fill out teaching staffs.

✦ Identify scientifically oriented students early; prepare them to meet admissions requirements of engineering schools; encourage them across the dangerous chasm between high school and college where 50 per cent of those with college ability are lost.

GOVERNMENT SHOULD:

✦ Keep pace with private wage scales.

✦ Assign draftees with technical training to those agencies that need them, such as the National Advisory Committee for Aeronautics.

✦ Provide untrained or semi-skilled draftees to groups where they can relieve trained men of routine tasks.

✦ Train "permanent" personnel who demonstrate scientific inclinations.

✦ Increase allotments to its technical agencies to include personnel advertising.

INDUSTRY SHOULD:

✦ Create and train a new working group of technicians who would be many steps above today's semi-skilled, semi-trained operators who could take over much of the work as well as the responsibility of the scientists and engineers.

✦ Make more efficient use of engineers and scientists who now spend part of their time on jobs that could be done by clerical help.

✦ Provide incentives for experienced engineers and scientists who must look to sales or executive positions for adequate financial recognition.

✦ Re-examine retirement policies that pension away many years of useful service.

✦ Not hoard scarce scientific personnel that can't be fully used.

✦ Offer technical personnel on a part-time basis to schools as teachers.

✦ Give science teachers and students an opportunity to improve themselves and make money by providing them with summer jobs.

✦ Extend its effort to interest students in scientific careers through such things as plant tours, sponsorship of science fairs and clubs.

✦ Take guidance counselors on tours of leading research and engineering centers to enable them to better advise students seeking careers in these fields.

✦ Increase individual productivity through increased use of automatic machinery.

✦ Encourage engineers to further their own development and efficiency through advanced education, membership in professional societies, etc.

Aerojet-General Corporation

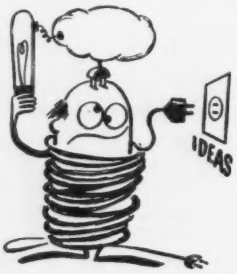
Azusa and Sacramento, Calif.

AEROJET-GENERAL Corporation, a subsidiary of The General Tire & Rubber Co., is the world's largest industrial organization devoted primarily to the rocket field—power plants, components, propellants, test facilities. Sales during 1956 exceeded $134 million, and 1957 promises to be perhaps the most significant year in company history.

At Sacramento, Aerojet's 20,000 acres are set between the San Francisco Bay region and the famed Lake Tahoe winter-summer playground. The San Gabriel Valley (Azusa plant) affords uncrowded suburban living only minutes from the heart of Los Angeles.

With nine operating divisions, Aerojet offers a variety of challenging assignments for engineers and scientists at all levels of experience. The following are some of the things *you* might do at Aerojet; for further information please write to the Director of Scientific and Engineering Personnel, Box 296, Azusa, Calif., or Box 1947, Sacramento, Calif.

THE ELECTRICAL ENGINEER

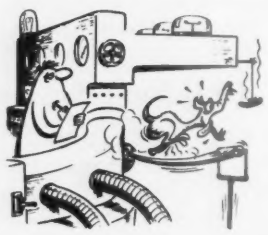


Design control systems, servomechanisms, and rotating machinery to meet the special requirements of rocket engines and guided missiles.

Design a variety of electrical equipment for shops, buildings, and test installations. Design and apply new types of test instrumentation.

Design power and communication systems for both production and testing facilities.

THE MECHANICAL ENGINEER



Design and develop pumps, valves, control and propellant systems for huge new liquid propellant rocket engines.

Design and test a variety of thrust chambers, turbines, injection systems, and servomechanisms.

Conduct studies of ignition, combustion phenomena, heat transfer, cooling, vibration, and thermal shock.

THE ELECTRONICS ENGINEER

Design and develop infrared detection, tracking, and guidance systems.

Design and develop missile guidance, aircraft search, tracking, control, communication, and gunsight systems.

Design magnetic circuits and amplifiers and data recording and processing equipment.

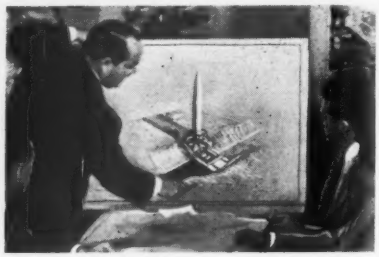
Perform electronic simulation of control systems using analog computers—analysis and synthesis.

Design and develop thrust reversers for jet engines.

Design and test underwater jet engines and other devices.

Design special equipment for high-pressure, high-temperature, and high-speed operation with highly corrosive materials.

Design test equipment and production machinery. Conduct analyses of, and prepare design modifications for, coordination of complete systems.



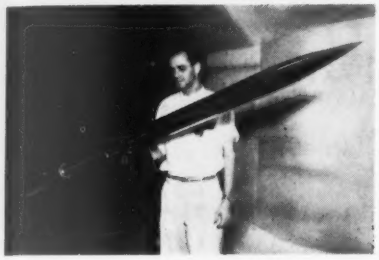
THE CHEMICAL ENGINEER

Design new processing, production, and handling equipment for different types of propellants, both liquid and solid.

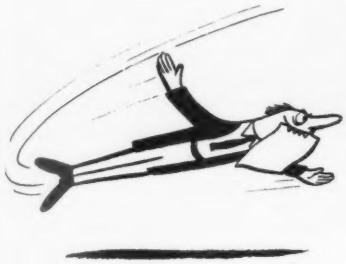
Develop, simplify, and improve techniques and procedures for propellant processing, production, and handling.

Compare and evaluate the advantages and disadvantages, the costs and applicability, of different materials and processes.

THE AERONAUTICAL ENGINEER

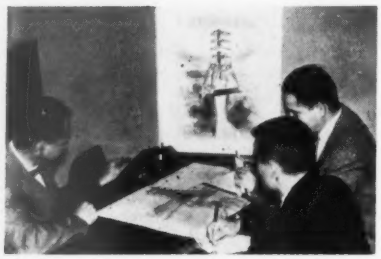


Investigate missile static and dynamic stability, control, pressure distribution, drag, aerodynamic heating, aeroballistics; duct flow, mixing, flow interference, thrust reversers; exceptional stresses and loads on unusual structures and materials.



Design and conduct analyses of inlet diffusers, nozzles, turbines, compressors.

THE CIVIL ENGINEER

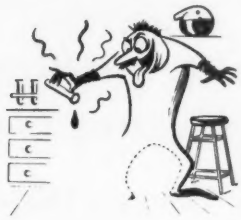


Perform layout and design work for large test structures and for the special buildings and installations required in the manufacture and testing of both liquid propellant and solid propellant rockets.

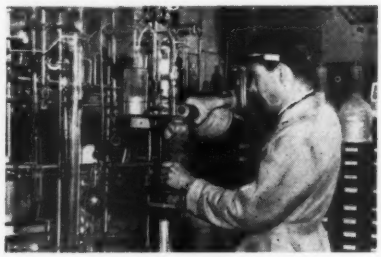
Plan site utilization and production facilities for testing and manufacturing installations.

Prepare design criteria for test equipment and special buildings.

THE CHEMIST



Conduct studies and analyses of new liquid propellants. Conduct studies related to the formulation of new solid propellants.



Conduct studies related to kinetics, inorganic synthesis, or high polymers.

Investigate a variety of problems in the fields of organic, inorganic, analytical, and physical chemistry.

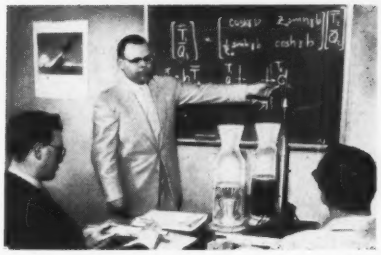
THE METALLURGIST

Conduct studies, analyses, and tests of new materials for possible use in advanced rockets (conditions involve high temperatures, high pressures, high speeds, and highly corrosive liquids and gases).

Conduct studies and analyses of new metallurgical processes for possible use in rockets or rocket test equipment.

Conduct nondestructive testing, including ultrasonic and x-ray.

THE PHYSICIST



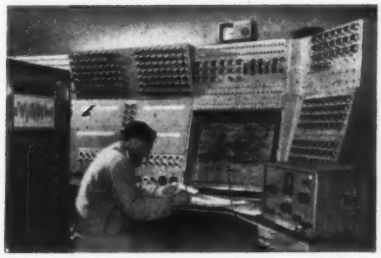
Investigate special guidance techniques, systems, and devices.

Conduct studies and experimental work in the fields of optics, and infrared and other types of radiation.

Conduct studies related to the design of nuclear equipment. Study problems in combustion, fluid dynamics, acoustics, elasticity, vibration, and heat.

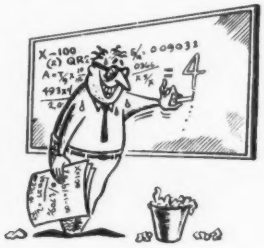
Develop new instrumentation systems and techniques.

THE MATHEMATICIAN



Develop mathematical analyses for various types of rocket control systems.

Perform mathematical analyses for new and intricate control systems.



Develop equations and methods for analog and digital computer operation.

Apply mathematical techniques to the solution of various system and component design problems.

Aircraft Gas Turbine Division

General Electric Company

Flight Propulsion Laboratory and Jet Engine Center, Cincinnati, Ohio

HERE's an opportunity for professional men with diverse engineering and scientific skills to join an operation that is now expanding to meet tomorrow's needs. Major achievements in the year just past include the design, development, and manufacture of the J79—the jet engine that delivers most thrust per pound of weight of any engine in its power class; and the CJ805—for use in the world's fastest commercial, medium-range transports. Another outstanding accomplishment in 1956 was the completion, from design through manufacturing, of the first-stage rocket engine for Project Vanguard.

$100,000,000 Facilities

You'll have the most advanced privately owned propulsion laboratory in the world to aid you. The General Electric Company has in full operation today, at the Evendale Development Center, facilities and equipment valued at more than $100,000,000—all built and equipped since the beginning of 1950. And more than half of this investment is exclusively in research, development, and test facilities.

Advanced Engineering

Flight propulsion engineering is advanced in every sense—stimulating, demanding, tough, and immensely rewarding to able men. You can rise fast and go far in Flight Propulsion Development at GE. And the company will help you all the way.

Professional Development

GE acquaints engineers joining the Aircraft Gas Turbine Division with all phases of the work (research, design, development, and test). These appointments are *working assignments* in various sections, lasting about four months each. They may be interrupted at any time by a *permanent* assignment, if a man decides early on his major field of interest. Salaries for engineers entering the Technical Career Development Program are not set at any one figure, but depend upon educational background and previous experience.

Graduate Study Plan

Speeding the professional development of its professional staff is a definite GE policy, practically expressed through individual counseling, technical seminars, a Full Tuition Refund Plan for graduate study leading to advanced degrees. Participation in professional meetings and presentation of technical papers are encouraged with AGT-GE paying necessary expenses.

Work With Experts

. . . But the most important "educational" assistance of all that the company furnishes young professional men is *contact with GE's expert propulsion team.* Men work here in small groups with frequent consultation available with recognized authorities in this field.

Status of G-E Engineers

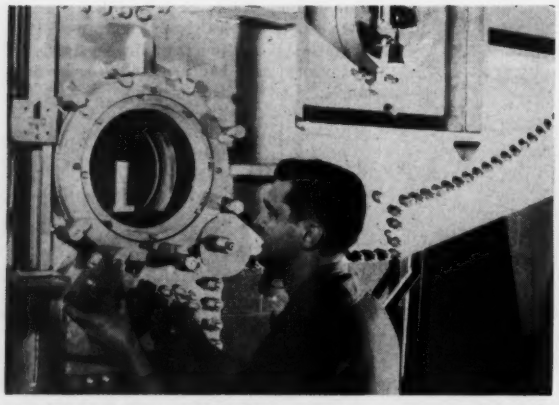
These include respect and appreciation of his professional status with competent assistants doing the routine work. Salaries are high and based on experience, education, and performance.

Openings for Graduates

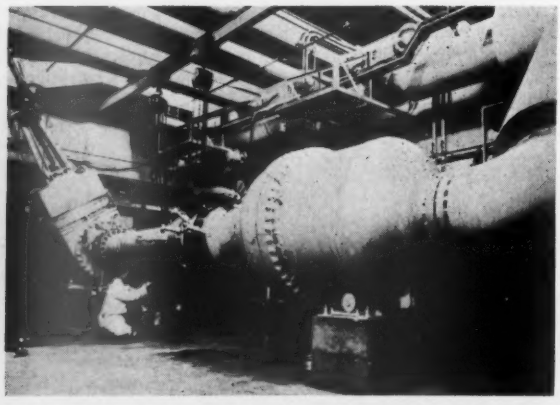
- Design and development of new and improved jet engine components, controls, accessories, and complete engine systems.
- Preliminary design of conceptual advanced propulsion systems.
- Design of special tooling, creation of specialized manufacturing and fabrication processes.
- Application engineering and performance analysis of the J79, CJ805, Project Vanguard, advanced jet engines, and nuclear and rocket systems.
- Create designs for high performance operation; provide data on aerodynamic design and performance; and conduct theoretical and experimental investigations of designs created.

Openings in both Malta, N. Y., and Cincinnati, Ohio.

For further information, please write to:
Mr. Don Cress
Technical Placement Bldg. 100
Aircraft Gas Turbine Division
General Electric Company
Cincinnati 15, Ohio



PORTHOLE TO TOMORROW. This new supersonic wind tunnel has been installed at the General Electric Company's Development Laboratory at Evendale, Ohio, to work on tomorrow's problems in the rocket and jet engine field. Air rushes through this tunnel at over 18,000 miles per hour.



COMBUSTION TEST CELL. One of General Electric's combustion test facilities, used to test new combustion systems for future rocket and jet engines. It is shown in the final stages of preparation prior to a burner test. The large tank in the foreground serves to straighten air flow for entrance into test section.

Arma

Division of American Bosch Arma Corp.

Roosevelt Field, Garden City, Long Island, New York

Post-Graduate Workshop

THE ARMA Post-Graduate Workshop for young engineers—is a major reason why career-minded engineers select Arma—and why Arma selects young engineers like you for your professional potential. For Arma invests time and money in comprehensive training programs to help you develop that potential—and make your transition from campus to industry a good one.

At Arma you will have time to survey your interests and aptitudes before selecting your field—a choice enriched by the wide variety of projects and skills that have made Arma a leader in electronics and electromechanical instrumentation.

On-the-Job Training

You begin your career on a sound foundation with Arma. Three two-month rotated assignments give you opportunities to look into different areas of activity—and assignments in missile guidance, project engineering, product engineering, and research and development further assist your development.

You'll work in digital computers and analog, servomechanisms, gyroscopics, inertial guidance, missile control systems, fire control systems and many other fields of instrumentation—learning about them in anticipation of your eventual assignment.

Professional Development

Your full professional capacities are developed along with the technical. Survey courses, lectures and round-table discussions are part of your training. Seminars and conferences develop your leadership abilities. All the while, you get automatic salary increases—and your progress backed by the stability and entire resources of Arma.

Personal Development

At Arma you will associate with men of unusual achievement in an atmosphere of technical sophistication. Nine outstanding colleges are within easy reach, and Arma encourages and subsidizes further education for engineers on all levels. Time and resources are available for you to make original contributions to technical publications, and professional society membership is subsidized.

Relocation assistance is available and in many instances expenses paid when you move your family to Long Island. Suburban life here is famous for ideal pleasure-living—and is within minutes of the plant. In addition, you are close to the educational and recreational facilities of New York City.

Your future career is backed by Arma's stability and its proven record of pioneering technical progress. Your best future is with Arma.

See the Arma Representative when he visits your campus, or send inquiries to:

Mr. Charles S. Fernow
Administrator of Technical Education
Arma
Division of American Bosch Arma Corporation
Roosevelt Field, Garden City, Long Island, N. Y.

Just one of the modern buildings in suburban Long Island that make up the Arma Division of American Bosch Arma Corporation, a company with 38 years of proved accomplishment in complex electronic and electro-mechanical precision instrumentation

Applied Physics Laboratory
of The Johns Hopkins University
Silver Spring, Md.

The Applied Physics Laboratory is a recognized leader in the field of research and development of guided missiles. It has gained its position in this highly competitive field through a program of accomplishment that has seen the development of the Terrier, Talos, and Tartar guided missiles—weapons which are fast becoming an integral part of the nation's defense arsenal.

THE work of the Applied Physics Laboratory began in the early 1940's when The Johns Hopkins Univeristy, at the request of the Office of Scientific Research and Development, established the Laboratory to carry on development of the radio proximity (VT) fuze for artillery shells. This effort was highly successful, and proximity-fuzed shells were used with telling effect by the Fleet during the last two years of World War II. The fuzes were adapted for use by the Army and also utilized by the British, playing an important role in the defeat of enemy V-1 missile attacks on England.

By the summer of 1944 it became evident that a radical approach to the problem of antiaircraft defense was needed. The enemy's suicidal tactics and the advent of high-speed planes during the latter phases of the war pointed up a new type of threat against which conventional defense measures were rapidly becoming ineffective. At the request of the U. S. Navy Bureau of Ordnance the Laboratory undertook a study of the problems posed by the new threat and recommended antiaircraft guided missiles as a solution.

Program Scope

For the past ten years the principal effort of the Applied Physics Laboratory has been devoted to the development of guided missiles under a broad program having the code name "Bumblebee." Since the early days when it had 50 staff members, the Laboratory has steadily grown into an organization having a staff of 1300—of whom 500 are professional engineers and scientists.

In 1945 techniques for launching, propelling, and guiding a supersonic missile were wholly unexplored. As a first step the Laboratory established research and development teams in each of these fields, and university and industrial contractors having special skills were brought in to make a concerted attack on the many problems that had to be solved. Development facilities to furnish realistic data on the performance of missile component systems were built. These included the first large-scale supersonic wind tunnel and ramjet testing facility, electronic flight simulators, flight test ranges, and the development of telemetering to transmit accurately the action of missile components in flight.

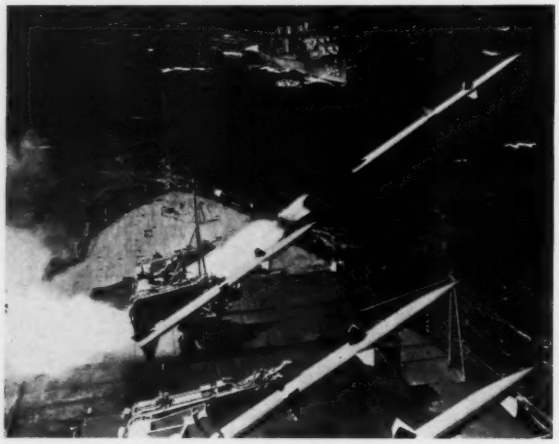
With this systematic and comprehensive effort, pioneering advances came rapidly. The first successful ramjet was flown by the Applied Physics Laboratory in June 1945. The first large booster rocket was developed in 1946. The first demonstration of control at supersonic speeds was made in 1947. Finally, fully guided supersonic flight was achieved in 1948. These accomplishments in the newly born field of guided missiles provided much of the fundamental understanding that has been the basis for a large part of the country's guided missile effort.

Having devised solutions to the essential problems of launching, propulsion, guidance, control, and warheads, the Laboratory took steps to design and build complete missile prototypes. This was accomplished with the aid of industrial "associate contractors" who also participated in the development programs under the technical direction of the Laboratory. The results were so manifestly successful that the Navy promptly placed direct procurement contracts for final engineering and production of the entire weapon system based directly on these prototypes and on specification requirements prepared by the Laboratory. Today, three missiles that grew out of the Bumblebee program are in various phases of production and development. The Terrier has gone through Fleet evaluation and is now a Service weapon; the Talos, a supersonic ramjet, has entered production; and Tartar, a new small, compact missile is in the process of final development.

The initial objectives of the Laboratory's guided missile program have been met; and a new phase, resembling in many respects the first development phase, has begun. The rapid growth of technology throughout the world has greatly increased the capability of the enemy to deal a devastating blow from the air. By the same token this growth has created the possibility of major extensions in performance of guided missiles for defense or retaliation. As a consequence, several new major programs have emerged from the basic Bumblebee program as prime objectives for the next five to ten years. There is no diminution in sight for challenging new technical problems.

In addition to the groups at the Laboratory responsible for applied research, development, and engineering of missiles and missile systems, a sizable fundamental research effort has existed since 1948, when the Research Center was founded.

Staff members of the Research Center conduct basic experimental and theoretical



The Navy's Terrier missile, developed by APL, fired from dual launcher

Research scientists isolate and study the hydrogen atom at the Applied Physics Laboratory

studies in selected areas of interest to the Laboratory; that is, in those areas that would offer the best hope of success in finding needed knowledge or those that would supply a breakthrough on the frontiers of scientific exploration that might lead to the initiation of new Laboratory activity.

Although there are no mutually exclusive groups in the Research Center, its work generally is apportioned in the broad fields of chemical, electron and microwave physics, and in fluid mechanics.

Professions

The Applied Physics Laboratory is primarily an organization of and for technical men and scientists—engineers, physicists, mathematicians, and chemists.

Two features distinguish the organization: the self-dependence of the professional staff, and the fluidity of relationships among the groups engaged in the many areas of technical endeavor.

The Laboratory has broken its total mission down into fields such as missile control systems, aerodynamics, and propulsion. To undertake the study of problems in these fields, teams of staff members drawn from all requisite professions are brought together. Each team maintains a balance between research at the one end and engineering of the final prototype at the other, with all necessary gradations of analytical and experimental design lying within the extremes. This results in an individual staff member's having a broad knowledge of the problem under attack, which leads to heightened individual creativeness. Similarly, technical freedom and cooperation among teams are fostered, insuring that the solution to any one team's problem will be a well-integrated and compatible part of the over-all objective.

The major professional activities in which the Laboratory is engaged may be broken down into the following five categories. In most of these there is a present need for additional staff members at all levels of experience.

1 *Electronic Design and Development*—guidance, control, telemetering, data-handling systems; analog and digital computers; radars; missile prototype design and flight test engineering; magnetic-amplifier and transistor applications; antennas, radomes, and microwave components.

2 *Aerodynamics*—composite design, wind tunnel testing, stability and control analysis.

3 *Mechanical and Aeronautical Design*—airframes and structures, mechanisms, launching and handling systems; ramjet engines, warheads.

4 *Applied Research and Analysis*

(a) Electronics—dynamic analysis of closed loop control systems; studies in electrical noise and interference phenomena; analysis of counter-countermeasures systems; analysis of external missile systems (computers, radars, etc.); flight test analysis; inertial guidance.

(b) Aerodynamics—interference phenomena, heat transfer.

(c) Mechanics—stress, flutter and vibration, acoustical noise, heat transfer.

(d) Propulsion—ramjet diffuser and combustor design.

(e) Operations research.

(f) Warhead effectiveness.

5 *Research*—combustion; solid state; infrared, electron, and microwave physics; excitation mechanisms; fluid mechanics.

Facilities

The buildings of the Applied Physics Laboratory are located in Silver Spring and Howard County, Md., conveniently situated with respect to residential suburbs of both Washington and Baltimore.

The buildings are modern and air-conditioned and are exceptionally well equipped for research and development activities. A complete environmental test laboratory, large electronic analog and digital computers, a burner facility for testing models of ramjet engines, and a hypersonic wind tunnel for research are but a few examples of the range and wealth of equipment available to the staff.

Living

The central position of Washington in the nation's cultural life is assured by the National Gallery of Art, the Smithsonian Institution, the National Symphony, and the memorials to Washington, Lincoln, and Jefferson.

Washington suburbs neighboring the Laboratory in Montgomery County, Md., include Silver Spring, Bethesda, Kensington, and Takoma Park. On the edge of Baltimore are Ten Hills and Hunting Ridge, and many staff members live in Catonsville.

The community has one of the highest standards of living in the country. Its advanced public school system has been rated by the Office of Education as one of the Nation's twelve best.

Centrally located on the Eastern Seaboard, the region is connected by rail and highway with such major cities as New York, Philadelphia, and Richmond. Scenic areas, such as the Skyline Drive, Harper's Ferry, the Shenandoah Valley, historic Williamsburg, Annapolis, the Chesapeake Bay, and ocean resorts on Maryland's eastern shore are within a few hours' journey.

Benefits

The major benefit programs offered by the Laboratory include paid vacation and sick leave, pension and group life insurance, educational benefits, a credit union, and recreational facilities and activities.

The vacation enjoyed by staff members varies from two to four weeks per year depending on staff level and length of service.

Educational assistance in the form of time off and remission of tuition is granted staff members taking college work, at the junior level or higher, in any of the area's schools: The Johns Hopkins University, University of Maryland, George Washington University, Catholic University, Georgetown University, and American University.

Organized but informal after-work recreation has been a part of the Applied Physics Laboratory since it was established. Today members have expanded their leisure-time activities to include bowling, golf, archery, chess, rifle shooting, private flying, choral singing, group and Laboratory-wide outings, and dances.

The new building of the Applied Physics Laboratory, located in Howard County, Md. (near Washington, D. C., and Baltimore)

Atlantic Research Corporation

Alexandria, Va.

In the Metropolitan Washington, D.C., Area

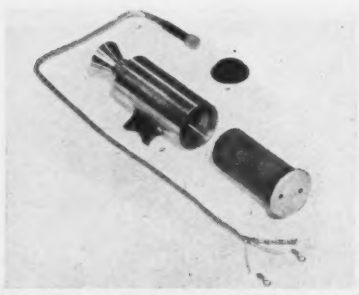
A Continued Story . . . . .

In last year's Careers Supplement, Atlantic Research described specifically some of the ways the professional training of scientists, engineers, and applied mathematicians is used in rocket engineering and related research and technology.

We are not repeating last year's story. Instead, we thought you would rather know more about our year's progress as an organization and learn a little about projects we have started this year or which we are now able to describe. If you missed last year's Careers Supplement, we will be glad to mail you a reprint of our 2-page section upon request.

Progress High Lights

Project Vanguard: The Martin Company of Baltimore, Md., has asked us to develop a small solid propellant auxiliary power rocket for the earth satellite launching vehicle. Four of the units will be used in launching the satellite, making us the supplier of more rockets for the launching than all other subcontractors combined. Two of our rockets will spin the third-stage satellite unit, and two will serve as retro motors for clean separation of second from third stage. Design development was completed in 90 days, and delivery of all production units called for should be completed when this supplement reaches you in February 1957.



The auxiliary power rocket developed for Project Vanguard required a full-scale development effort despite its small size. Designed for reliable performance in vacuum above the earth's atmosphere, it is approximately 5 in. long and $1^1/_2$ in. in diam and delivers 50 lb of thrust in 1 sec.

Continued expansion led to announcement in November of plans for a million-dollar new headquarters in a 40-acre parklike setting in suburban Virginia. Company activities increased 50 per cent in 1956; operations were at a $2 million annual rate at the year's end.

Iris Sounding Rocket: Under development for the Navy, the Iris is designed to carry a 100-lb instrument payload 200 miles above the earth's surface, and is intended as a successor to the 150-mile-range, 150-lb-payload Aerobee-Hi.

Arcon Sounding Rocket: In size, the Arcon is similar to the 40-lb-payload Deacon rocket that the Navy has used extensively for upper atmosphere research. Arcon's design extends the 6-mile altitude attained by the Deacon to over 60 miles, and with the same payload.

Terrier Sustainer: Although details are still classified, we can say that this Navy project promises a significant performance advance for the first guided missile to be put into Fleet service.

Thor Retro: An intermediate-range Air Force ballistic missile project which also calls for a retro motor; Douglas Aircraft has asked us to develop it.

Seat-Ejection Rocket: Rockets can be life-saving as well as death-dealing devices. The Air Force has asked us to work on a rocket for a device to help pilots escape from disabled airplanes.

Research: Numerous projects, government and industry-sponsored. Rocket fuel combustion fundamentals, basic studies of flame extinguishment, fluid dynamics in transient-state environments, chemical kinetics, vibration studies, dynamic mechanical measurement, and instrument development are examples. While Atlantic Research is very active in the rocket development field, its research and development projects span the entire physical science spectrum, and its functions range from fundamental research through product and process development to manufacturing and marketing.

Our work has kept us close to the frontiers of science, where opportunities are limitless for young scientists and engineers with good training and personal ability.

For information on career opportunities at Atlantic Research and/or to receive a copy of ARC's 1956 Careers Supplement reprint, write (including name of school and major subject) to:

Mr. Clarence Weissenstein
Atlantic Research Corporation
Alexandria, Va.

Battelle Institute

505 King Avenue, Columbus 1, Ohio

AS ONE of the world's largest independent research organizations, Battelle offers career opportunities in nearly all the sciences and technologies related to rocket and missile development.

Permanent staff openings are available for qualified aeronautical, mechanical, electronic, chemical, and design engineers. Attractive positions are also available for chemists, physicists, metallurgists, mathematicians, and computer technologists who would like to specialize in research in the fuels, materials, and control problems associated with flight vehicles.

At Battelle, you can virtually take your pick of research areas—and even of projects. You may choose engineering development, pilot-plant work, or bench-scale research. Or, should you prefer, you may concentrate on theoretical studies. Serving both industry and Government, Battelle interests are varied and ever-expanding.

Battelle does nothing but research—and this is one of its big advantages to a research careerist. Should you enter some phase of Battelle's research related to rockets or missiles, and later wish to change to, say, atomic power plant engineering, industrial product or process development, or consumer product research, the transition could be readily made.

All the Sciences

Battelle works in all the industrially useful physical sciences, many agricultural and biological sciences, and numerous highly specialized technologies. Each year more than 1000 research projects are conducted in the Institute's laboratories in Columbus; Frankfurt, Germany; and Geneva, Switzerland. The 3200 scientists, engineers, technologists, technicians, and service personnel associated with Battelle will be responsible for over $20,000,000 in research expenditures this year.

To encourage professional development, Battelle provides a free working environment. You, as a beginner on the Battelle staff, will work side by side with prominent technologists with whom you will be on a first-name basis. You will be given an assignment and suggestions for its execution, but no strict regimen will be laid down for you to follow. At every point, you will be encouraged to think for yourself—to make suggestions—to ask questions—to join in the team operation as a full-fledged member.

You will be given every opportunity to write technical papers, to participate in the committee work and meetings of technical societies, and to pursue your professional studies. Should you wish to take postgraduate work at nearby Ohio State University, Battelle will reschedule your working time and pay your matriculation and tuition fees.

Continuing Growth

Battelle conducts quality research and has a world-wide reputation for integrity and accomplishment. Since the Institute's founding in 1929, it has grown almost continuously, and its management has a strong growth philosophy. Indicative of this philosophy is Battelle's recent construction of the first complete, private center for atomic research.

Because Battelle is a growing organization, opportunities for promotion are great. And you can take your choice between advancement into managerial positions or advancement into posts of technical distinction.

Salaries are in keeping with going rates, and promotions and salary increases are on a merit basis. All the customary social, recreational, and health services are available. The Institute's insurance and retirement plan is recognized as one of the best in the nation and will provide you and your family with exceptional financial security. Metropolitan Columbus, a city of 610,000, is geared to the likes and interests of professional people.

To become a member of a research organization that is known throughout the world—that is a leader and a pioneer—that can offer you a permanent and satisfying career, write to Mr. R. S. Drum, Personnel Manager.

Beech Aircraft Corporation

Wichita, Kansas

SINCE 1932 Beech Aircraft Corporation has been recognized throughout the world as a leader in the field of aeronautics. These years of experience encompass all aspects of aeronautical design, development, and production.

Since its inception, it has been the policy of Beech Aircraft Corporation to pursue a vigorous and diversified program of research and development as well as production. This program has included:

1. Executive commercial aircraft
2. Primary, basic, and advanced training military aircraft
3. Personnel transport and liaison military aircraft
4. Guided missiles
5. Propellers (constant speed, full feathering, and reversing type)
6. In-flight refueling
7. Jettisonable fuel tanks and fire bombs
8. External stores
9. Self-propelled generator sets
10. Self-propelled units for ground support of guided missiles.
11. Target drones
12. Tow targets
13. Boundary layer control
14. Cryogenics
15. Mechanical propeller drives, powered by several engines

Beechcraft has produced more than 15,000 airplanes and thousands of propellers for military and commercial customers. In addition to being a prime contractor, Beech Aircraft Corporation's subcontract program has included production, and research and development contracts for Lockheed, Boeing, Republic, McDonnell, and General Motors. These contracts have included major engineering programs, such as the FICON project, and others of a classified nature, as well as mass production of major components for such aircraft as the T-33, RF-94C, B-47, RF-84F, F-101, F-84F, F-102, and F-3H. This diversification of experience permits Beech Aircraft Corporation to undertake with confidence any project in the aeronautical field whether it be the designing of a high altitude missile or a problem dealing with the handling of liquefied gases.

The Engineering Department of Beechcraft consists of hundreds of trained engineers and scientists who are organized into efficient, coordinated teams or groups having specific responsibilities and assignments. These teams are: Preliminary Design Group, Aerodynamics Group, Structures and Weight Control Group, Engineering Test Group, Engineering Loft, and Project Groups. These groups or teams are supplemented by the staffs and facilities of the Metallurgical Laboratory, Chemistry Laboratory, Electrical and Electronic Laboratory, Experimental Department, and Computer Group.

In recognition of the importance of the missile in the modern concept of the weapon system, Beech Aircraft Corporation has established a Missile Division in its Engineering Department to deal specifically with this specialized field of engineering. This Missile Division is staffed by a group of engineers and scientists recognized as some of the most able men in this field of activity.

The Engineering Department predominantly functions on the project system basis, wherein each project, upon completion of the preliminary design stage, is assigned to a group of competent engineers for final design work. Each Project Group, under the direction of a project engineer, is composed of engineers experienced in the design of airframe, propulsions systems, electrical and electronic systems, flight control systems, stabilization systems, and detail components essential to modern aircraft, missiles, and ground support equipment. Each Project Group has the capable assistance and complete cooperation of the specialized engineering groups and laboratories as required throughout the design and production of the end article.

Beech Aircraft maintains six facilities—three in Wichita; one in Herington, Kan.; one in Liberal, Kan.; and one in Boulder, Colo. The Boulder facility is primarily an engineering design and test facility which includes a 760-acre test site for classified projects.

Beechcraft's rapidly expanding research and production programs for both commercial and military aircraft have created an urgent need for experienced engineers. Benefits include top starting wages, incentive payments, and payment of relocation expenses. Beechcraft is recognized as a company sufficiently large to have diversification of products and work, yet small enough to insure recognition of personal ability and the opportunity to advance.

Beech Aircraft is interested in receiving inquiries from qualified engineers. All inquiries will receive an immediate reply and will be held in strict confidence. Write or wire Roy F. Kunz, Engineering Procurement Supervisor, Beech Aircraft Corporation, Wichita 1, Kan., or telephone collect at MUrray 3-4681, Wichita, Kan.

Bendix Products Division

Guided Missile Section

Mishawaka, Indiana

The Organization

THE Guided Missile Section of Bendix Products Division is a vitally important segment of the Bendix Aviation Corporation.

While it's backed by, and benefits from, the vast resources and facilities of Bendix Aviation Corporation, the Guided Missile Section is a compact, relatively small, autonomous organization dedicated solely to the design, development, and production of guided missiles.

Present plant facilities include three adjacent buildings: a recently constructed Production Facility Building, an Environmental Test Building and an Engineering Building.

Bendix is not only a pioneer in the field of guided missiles but today is the prime contractor for the important and successful Talos missile. As a result, here at Bendix Guided Missile there is literally an open field for advancement for ambitious young engineers who can accept the responsibilities that go with opportunity.

The range of technical job opportunities is far wider than in companies where guided missile work is a secondary project. Everyone you will be associated with at Bendix Guided Missile is first and foremost a missile engineer, and many of these engineers are ranked with the outstanding authorities in the entire industry.

Guided Missile Section engineering is divided into two interdependent departments—Department of Engineering and Department of Quality Control.

The Department of Engineering is headed by the Director of Engineering, who is in charge of all missile systems engineering. From his office come instructions and directives that govern the operation of the chief electronics engineer, chief fuel and hydraulic engineer, chief project engineer, chief weapons systems engineer, design and drafting chief, and the chief administrative engineer.

The Quality Control Department is under direction of the quality manager, who is responsible for test engineering, missile test, test equipment design, inspection, environmental test laboratory and reliability.

Personnel regulations in all departments are on an informal basis with the result engineers and other personnel are encouraged to discuss engineering problems with their superiors.

Job Opportunities

Under the broad classification of the Department of Engineering and the Department of Quality Control, Bendix Guided Missile offers almost unlimited interesting and challenging job opportunities in the following areas: systems analysis, guidance, telemetering, steering intelligence, component evaluation, missile testing, environmental testing, test equipment design, reliability, ramjet propulsion, and hydraulics.

Advancement

We sincerely believe that no other company in the guided missile field offers greater advancement opportunities for the young, ambitious engineer.

In the first place, the Bendix Aviation Corporation and all of its twenty-five divisions is essential as an engineering organization with an impressive list of "firsts" in every field in which it operates. Engineering ability always gets important recognition with Bendix.

As prime contractor for Talos missile, obviously the equipment and facilities with which you will work are unsurpassed, and your close association with key men of the industry will enable you to develop your natural talents more quickly and to a greater degree. There is no question about it—your opportunities are always bigger and better when you play in the "big league"—and Bendix Guided Missile is definitely "big league."

Ideal Location

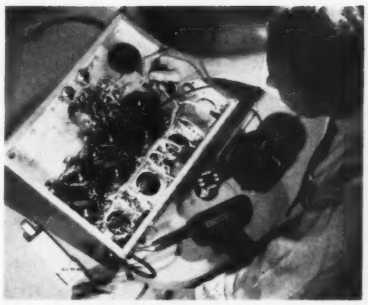
The companion cities of Mishawaka and South Bend have a combined population of 150,000, with over 73 per cent of the people owning their own homes. In South Bend's downtown shopping section you will find everything from large department stores to fashionable specialty shops.

At the same time you are right in the middle of one of America's ideal vacation locales. Within a radius of fifty miles of the South Bend-Mishawaka area there are several hundred lakes as well as swimming and sailing on nearby Lake Michigan.

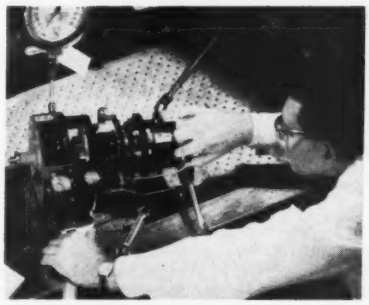
Then, too, there are schools within easy distance wherever you live in this attractive area—77 elementary schools and 12 high schools.

There is also opportunity for advanced study of direct help to your profession at Notre Dame University. And for the big city shopping trip, shows, or just a good time, Chicago is only a two-hour ride from South Bend.

Here, indeed, at Bendix Guided Missile is where you can combine ideal living conditions with outstanding job opportunities. So that you may investigate thoroughly the advantages of becoming a Bendix Guided Missile engineer, we have prepared a thirty-six-page book, "Your Future in Guided Missiles." We think it will answer your every question about job opportunities, living conditions, and special employee benefits.



TEST EQUIPMENT—Test equipment engineers are engaged primarily in the design of specialized missile check-out equipment



HYDRAULIC DESIGN—Hydraulic power unit undergoing adjustment and setting prior to severe testing

STEERING INTELLIGENCE—Steering Intelligence Engineers are concerned with refining guidance equipment for greater missile accuracy at greater ranges

It's yours for the asking. Just drop us a line today and a copy of "Your Future in Guided Missiles" will be mailed to you promptly.

Bendix Guided Missile Section
Bendix Products Division
410 Bendix Drive
Mishawaka, Ind.

Bell Aircraft Corporation

Weapon Systems Division

Post Office Box One, Buffalo 5, N. Y.

AT BELL Aircraft, established as one of the industry's leaders through twenty years of aeronautical design, research, development, and production, you will become a member of a team of engineers, scientists, and technicians proud of their heritage as pioneers in the fields of rocket propulsion and guided missile weapon systems.

The rapid technological advances demanded by aviation's customers have caused performance requirements to soar to previously undreamed-of levels, and, consequently, the industry has had to assume new responsibilities. Bell Aircraft has accepted these responsibilities, and since the end of World War II has devoted its efforts toward the development of new and revolutionary equipment. These developments soon required many specialized skills not previously associated with aircraft development, so that Bell changed from an aircraft production organization into one for research and development.

Accompanying this change was a demand for many more specialized skills in all fields of engineering, so that Bell Aircraft today is a large team of engineers and scientists actively engaged in the development and production of new concepts in weapon systems and components vital to defense and the new age of automation. Included are the engineers responsible for these new concepts and for following them through the various phases of development. Seasoned by experience, these engineers and scientists have become experts and authorities in their respective fields of endeavor.

This team, however, is not sufficient for the demands of present development and production schedules. This fact, and our ever-increasing research and development program, provide excellent openings for engineers and scientists desirous of "ground floor" opportunities. Engineers with degrees in aeronautical, mechanical, civil, electrical, electronic, chemical, and metallurgical engineering, and scientists specializing in physicis, mathematics, chemistry, and nucleonics, are needed at Bell Aircraft.

Test firing a simulated missile in a dive attitude

The Weapon Systems Division is actively engaged in the design, development, and production of several missile weapon systems and missile components for other manufacturers. The Weapon System Concept, adopted by the military services, delegates more development responsibility than ever before to the manufacturer. For example, the RASCAL Weapon System, produced by Bell Aircraft for the Air Force, is a total entity consisting of the guided missile together with all its related equipment, its supporting facilities, and the services required to deliver the missile to its target. The development and production of such a system require the combined skills of a great many different types of engineers and scientists.

Preliminary Design Engineers conceive, analyze, and evaluate new and advanced concepts for missile weapon systems, rocket engines, guidance systems, control systems, and miscellaneous components. They prepare technical proposals in the form of drawings, charts, graphs, and other media, and carefully analyze new designs to establish desirable configurations to achieve the missile requirements. Separate design groups handle the design and development of the major components and their integration into the propulsion, guidance, and control systems, and then into the missile weapon system as a unit. The design engineer therefore must have a clear concept of the many technologies involved in the development of a missile weapon system. Unlimited opportunities are offered to engineers with foresight and creative abilities at Bell Aircraft in the field of preliminary design.

Rocket Engineering at Bell Aircraft started in 1945 with the world's first supersonic airplane, the X-1, powered by a 6000-lb thrust engine. The rocket engineers deal with design and development

problems associated with the major components of rocket engines, including thrust chambers, high speed and turbine and pump drive units, tanks and pressure vessels, rocket engine controls, and accessory valves and regulators. Testing of the rocket engines and components is done in thirty test cells at the Wheatfield plant, and others at another local test facility. Research is carried on in the several rocket engine laboratories on combustion, heat transfer, propellant chemistry, materials, and fabrication processes.

Aerodynamicists at Bell Aircraft have evolved the configurations for the rocket-powered supersonic guided missiles that have distinguished Bell Aircraft's activity in the past. As an aerodynamicist at Bell, you will become a member of a team working on the development of airframe design for tomorrow's guided missiles and supersonic aircraft. Wind tunnel facilities that produce flow velocities up to Mach 4.0, and a schlieren system for flow observation are available. An engineering aid designed and built by Bell Aircraft is the electromechanical computer, especially suited for the complicated aerodynamic parameters that are handled only with difficulty by REAC or digital computing equipment. Gear shifting mechanisms make it possible to change scales easily, enabling the solution of performance problems for aircraft of widely different sizes, velocities, and altitude requirement.

Servomechanisms, the muscles of piloted aircraft and guided missiles, are the concern of engineers assigned to the Servo groups. Personnel required in this field cover many types of engineering, especially hydraulic, electrical, mechanical, optics, mathematics, design, development, and kindred techniques. Here the work involves the conception, design, development, testing, and manufacture of servo systems in any degree of complexity from simple remote positioning mechanisms to servo pilots for all kinds of aircraft and guided missiles.

To assist the servo engineer is an Analog Simulation Laboratory containing one of the country's most elaborate arrays of Reeves Electronic Analog Computers. Here the dynamic analyses of complex large-scale systems are conducted, including study, analysis, and preparation of problems for computer solutions, design of computer schematics, problem patching, computer operation, and interpretation of results.

Electronics Engineers at Bell Aircraft provide the sensitive "brain power" for guided missiles and many other products. Within this group are found specialists in designing prototype electronics equipment to meet manufacturing requirements. Systems are designed to provide adequate telemetering information in accordance with flight plans for various guided missiles. Automatic launch equipment is developed along with guidance systems and equipment, antennas, radomes, and microwave components, radar design, computer design, autopilot modifications, and remote control equipment.

Major emphasis has been placed on a wide range of automatic control devices. A number of automatic stabilization systems have been perfected for guided missiles, aircraft, and helicopters. As an outgrowth, a variety of high-pressure hydraulic-control components have been designed which are being adapted to the automation of precise operations. These and other electronic systems are being produced by the electronics engineers at Bell Aircraft in keeping with the demands of automation for miniturization, reliability, and flexibility.

Engineers with background in mechanical and aeronautical engineering, mathematics, statistics, and physics will find an intriguing array of research and development work in the field of *advanced analysis*. This field involves dynamic analyses, aeroelastic analysis and tests, wind tunnel and flight tests, structural analysis, dynamic load tests, and the design and testing of dynamic models. The applied mathematics, computation, and analog and digital computer groups are concerned with mathematical operations, computation, and graphic presentation. Physical problems are studied and expressed in mathematical form so they can be set up for general methods of solution. The application of scientific principles and methods of investigation to problems of system operation is handled by engineers and scientists of the operations analysis phase. Another responsibility of an engineer or scientist is data processing and analysis, handling a wide variety of problems arising within the Weapon System Division.

Laboratory Engineers provide testing services throughout the fabrication of components, installation into systems, check-out of the completed missile or aircraft, and subsequent flight tests. Bell Aircraft policy dictates that quality must be built, not checked, into its products, so that careful component checking and testing is conducted to insure quality components complying with applicable standards and specifications. Preflight testing of the missile systems is done at the Missile Laboratory and at Bell's rocket test facility nearby. Flight testing takes place at Holloman Air Development Center, N. Mex. As a laboratory engineer you may be assigned to any of these facilities.

Research and Testing Laboratories are maintained in accordance with Bell's policy of providing from-start-to-finish engineering facilities. These laboratories, employing over 300 engineers and technicians, make Bell Aircraft self-sufficient in the processing and solution of research problems, and offer consultation, advice, research, and evaluation services throughout the organization in the fields of chemistry, metallurgy, materials and processes, electromechanics, hydraulics, vibration, static load testing, environmental testing, instrumentation, measurements, and calibration.

The Environmental Laboratory tests equipment and components expected to encounter extremes of climate or inclemency of weather. Here the walk-in altitude chamber, with a volume of 435 cu ft, can vary temperature conditions from −90 F to +200 F, relative humidity from 25 to 95 per cent, and pressure altitude equivalent to 90,000 ft.

The Chemical Laboratories are well versed in infrared and ultraviolet spectroscopy and in mensuration techniques. Fuels, reaction kinetics, polymerization, viscosities, conductivities, and many related chemical and physical phenomena are subjects of continual interest. Bell has one of the country's largest corrosion test laboratories, now devoted to testing rocket oxidizers.

Some of the other services at the laboratories include x-ray work, loading and testing, stress and strain measurements, proof-testing of pressure vessels, and centrifugal tests. One of the two largest centrifuges in the world devoted to equipment testing is found in Bell's Static Test Laboratory. It operates at speeds up to 235 rpm, 135 g, and is capable of testing up to 500 lb of equipment mounted on its 16-ft arm. Tests combining altitude, temperature, and gravitational forces are possible on this machine.

Your Future Is at Bell Aircraft, for here you will find assignments commensurate with your educational background and experience, tailored to your individual preference and interests.

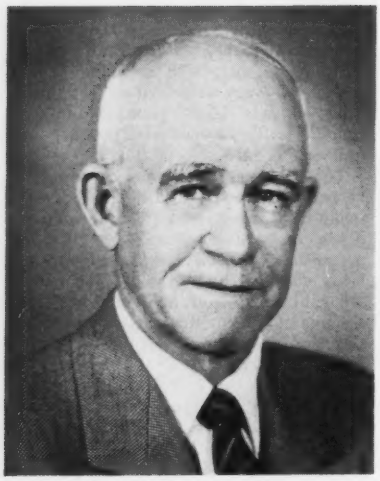
For information on the operations and facilities, and the complete story of your future with Bell Aircraft, ask for our descriptive brochure.

Write Manager, Engineering Personnel, Dept. K-S, Weapon Systems Division, Bell Aircraft Corporation, P. O. Box One, Buffalo 5, N. Y.

Launching the Bell Aircraft air-to-surface missile "Shrike"

Bulova Research and Development Laboratories

62-10 Woodside Ave., Woodside 77, N. Y.



Gen. Omar N. Bradley

THE Bulova Research and Development Laboratories, Inc., a wholly owned subsidiary of the Bulova Watch Co., was organized in 1950 in order to intensify and diversify Bulova's World War II development and production experience in airborne instrumentation and antiaircraft artillery fuzes.

Since then, under the guidance of General Omar N. Bradley, chairman of the board, and Edwin F. Shelley, vice-president, the Laboratories have concentrated on the research and development of precision defense products where highly accurate performance is achieved through technological innovation and at a minimum cost in weight and volume. Significant recent achievements include: novel electromechanical fuzes for shells, bombs, rockets, and guided missiles; safety and arming devices for the Sparrow, Terrier, Talos, and Tartar antiaircraft missiles; a solid propellant actuated gyroscope for the Dart antitank missile; airborne camera systems and automatic aperture controls; a precision closed-loop altimeter; fuzed quartz delay lines; a mechanical shipboard launching display for Terrier. In addition, Bulova is contributing to the National Preparedness Program by virtue of (1) a multimillion-dollar automation research and development program wherein a reappraisal of the entire process for the manufacture of quartz crystals has been undertaken for the Signal Corps; and (2) the development of production line techniques for sensing elements used in the Sidewinder infrared seeker.

• Of special interest to readers of this ARS Supplement will be recent activities of the Advanced Systems Department. This group was formed in 1955 for the purpose of conducting research and development in the fields of guided missiles and complex electronic systems. This effort was organized around a group of engineers and scientists having considerable prior experience in the aircraft and electronics industry in connection with numerous missile system projects. The continued growth and success of this group are assured by the extensive experience of other Bulova departments in the design and development of advanced electronic and electromechanical components and by virtue of its support by extensive laboratory, experimental shop, and low-cost, high-precision manufacturing facilities of the parent organization.

Since its inception, the Advanced Systems Department has centered its activities in (1) the field of small-bore guided rockets and guided missiles incorporating novel guidance techniques; and (2) broad-spectrum system studies in the fields of passive homing for missiles and interceptors and integrated all-weather reconnaissance. The initial missile design study efforts have materialized into a contract from the Department of the Army for the study of a recoilless rifle launched, post-firing corrected projectile involving the full gamut of missile technology: guidance, control, aerodynamics, jet propulsion, operations research, etc. The effort has progressed to a point where a flight test program is being prepared for substantiating the novel post-firing correction technique.

The Advanced Systems Department requires for its expansion specialists in infrared techniques, microwave propagation, operations research, and missile design

The study for USAF of electromagnetic homing techniques, of which the first phase has been successfully completed, involved various aspects of passive radar and infrared technology: propagation, receiver design, direction finding, identification, etc. It is expected that this study effort will continue in additional problem areas and that experimental and hardware work, based on the findings of the study, will follow. A current USAF study contract for the study of an integrated all-weather reconnaissance system is leading in the same direction. Here novel system concepts regarding the effective utilization of a multiplicity of sensors, covering various parts of the electromagnetic spectrum, are being evolved. It is expected that significant contributions to the translation of these concepts into effective hardware will be made by the Bulova Camera Division, headed by Brig. Gen. George W. Goddard, USAF (Ret'd.).

The system analysis and synthesis work performed under the above contracts is predicated on a combination of the latest electronic and missile technology with an optimal use of statistics, decision theory, information theory, etc. In addition, the operational situation is thoroughly analyzed in each case in order to insure systems which are optimum on the basis of cost-effectiveness considerations and their ability to be efficiently integrated into future military environments. To insure maximum utilization of the experience and talents of each individual, judicious and successful use is being made of the precepts of group creative thinking.

• The activities of the Advanced Systems Department are now expanding at an ever-accelerating pace, primarily in the above-mentioned project areas. This will require the addition to the present nucleus of about fifteen engineers and scientists, individuals interested in applying the latest techniques to the synthesis, analysis, and development of novel and operationally optimum electronic and missile systems. The opportunities for advancement and professional development at Bulova in general, and its Advanced Systems Department in particular, are deemed to be exemplary—this young and dynamic organization is led by a core of progressive, professional-minded veterans of the missile and electronics business and provides, it is believed, the only opportunity to work on a prime missile system project in New York City. Extensive opportunities for advanced study are available at Columbia University, New York University, the Polytechnic Institute of Brooklyn, Cooper Union, etc., while active participation in the affairs of professional societies is facilitated by headquarters' location there and the concomitant concentration of national meetings.

The Jet Propulsion Laboratory

California Institute of Technology

Pasadena, California

For more than 15 years the achievements of the Jet Propulsion Laboratory have paced our nation's progress in the field of guided missiles. The Laboratory has pioneered studies in the physical sciences, the results of which are now making possible the investigation of space itself.

. . .

FUNDAMENTAL contributions made by the Jet Propulsion Laboratory enabled it to develop the first jet-assisted takeoff units, JATO; the first high-altitude sounding rocket, WAC Corporal; the first two-stage rocket, Bumper WAC; the first operational guided missile, Corporal; and other important "firsts" which have not yet been divulged. Today, as in the past, men and women of the Jet Propulsion Laboratory are exploring new scientific frontiers.

The Jet Propulsion Laboratory functions under the Department of Army, Ordnance Corps, and is a significant example of the university-operated, government-owned installation. The staff and management, approximately 1700 professional and technical personnel, have a threefold mission: (1) To originate and develop primary missile systems; (2) to conduct fundamental research investigations in the physical sciences, both for future application in weapon system programs and for immediate utilization by other research, development, and production facilities; and (3) to conduct feasibility and evaluation studies for the Department of Defense.

From the end of World War II until 1949, the Laboratory conducted preliminary developmental programs to obtain experience and scientific data necessary for long-range plans. During the following five years a major development effort was devoted to the Corporal surface-to-surface guided missile. This weapon is now being produced by industry and is one of the regular Field Forces weapons. But, even before the Corporal was finalized, work was started on an entirely new missile system, the Sergeant. This new system, which takes advantage of advanced JPL developments, will absorb a considerable part of the engineering effort for the next few years. A significant effort, however, is already being devoted to other missile programs.

Extensive basic research investigations of promising new theories are being continued on an ever-increasing scale. Studies are conducted in such fields as aerodynamics, chemistry, physics, metallurgy, hydraulics, missile engineering, electronics, nuclear energy, etc. More than half of the Laboratory's personnel is engaged in studies pertaining to electronics and missile guidance and control.

The Jet Propulsion Laboratory frequently acts in an advisory capacity by conducting studies for the Army Ordnance Corps, whereby current and anticipated Ordnance projects and programs are reviewed for technical feasibility. In addition, many senior staff members of the Laboratory are permanent members of advisory and planning committees administered by the Department of Defense.

The results of JPL studies are disseminated in report form to government-sponsored research and development contractors and the military. Results of unclassified studies are made available to interested educational institutions and to industry. Engineers and scientists are encouraged to publish the results of their investigations in open literature and to attend scientific and technical symposiums.

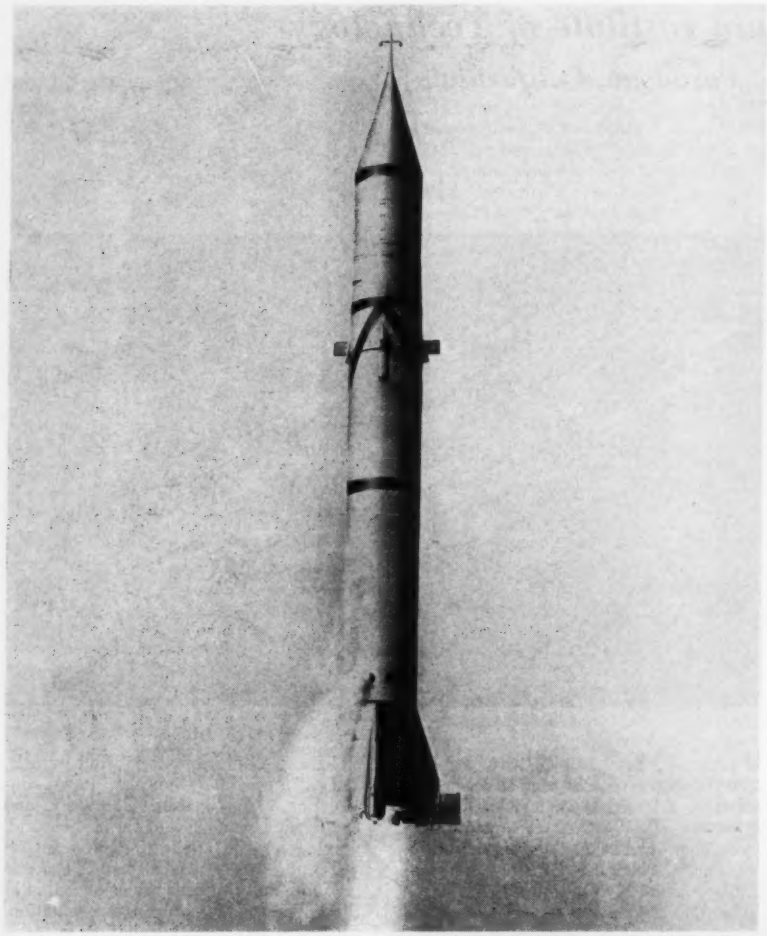
Principal Laboratory facilities cover 80 acres in the foothills of the San Gabriel mountains about 8 miles from the California Institute of Technology campus in Pasadena. The JPL installation includes 20-in. and 12-in. supersonic wind tunnels, and a hypersonic tunnel is under construction. Combination laboratory and test facilities, among the best in the world, provide for the application of basic research data to controlled tests. Processing units and test cells are also located at the Laboratory for propellant evaluation. An instrumentation installation is maintained for the recording and reduction of test data. Much of this equipment has been designed by Laboratory staff members to fulfill specific JPL requirements. Included are digital and analog computers and mobile recording units.

Static and flight-test facilities are maintained at Edwards Air Force Base, Calif.; White Sands Proving Ground, N. Mex.; and Patrick Air Force Base, Fla.

JPL has clearly demonstrated its leadership in the research and development of rockets and guided missiles. Present programs and facilities provide unique opportunities for research scientists and engineers. The future exploration of uncharted areas will provide still greater opportunities in this important frontier of science. Those applicants who are citizens of the United States and who are deemed professionally competent become welcome associates, thereby insuring for themselves an active and satisfying role in the contribution of science to America's defense. Your correspondence is invited.

Chrysler Corporation—Missile Operations

Personnel Department, P. O. Box 2628, Detroit 31, Michigan



ONLY a handful of men in the world today have more than five years' experience in missile research and engineering. Yet in no other area of science is such accelerated progress being achieved. Never before has a new field opened up so fast or commanded such undivided support from both Government and industry as ballistic missiles.

Chrysler Missile Operations has contracts with the Government involving responsibilities in the design, development and fabrication of the Redstone, Jupiter, and Fleet Ballistic Missile Systems.

The phenomenal advances being recorded at Missile Operations daily reflect the counsel of the most respected names among the missile pioneers, plus the imagination, talent, and hard work of a corps of young engineers who have taken up the challenge of this dramatic new field.

No field of science offers the challenge—the excitement—the encouragement—that the field of ballistic missile holds forth today for the young engineer. Chrysler Corporation-Missile Operations offers you the opportunity to achieve leadership in any or all aspects of missile research, development and production.

We invite your inquiries in the following fields of engineering:

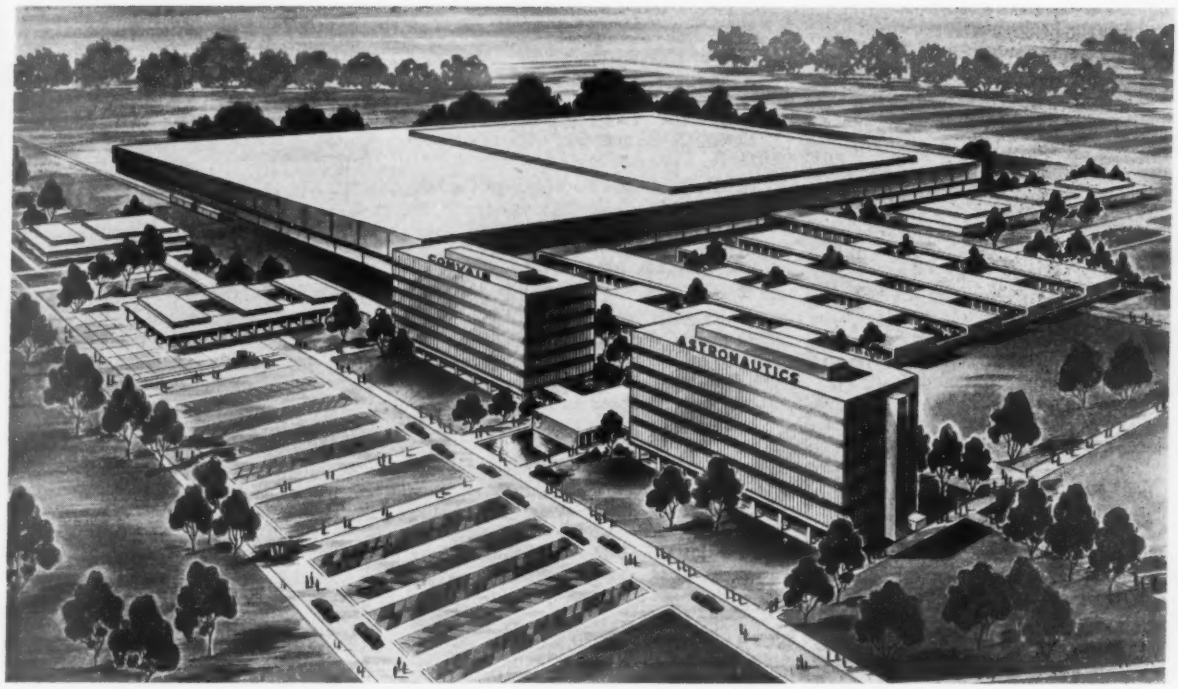
Electrical
Mechanical
Metallurgical
Aerothermodynamicists
Physicists
Structures analysts
Electronic
Aeronautical
Aerodynamicists
Mathematicians
Stress analysts
Weight analysts

This 32-page brochure, "Assignment with a Future," tells more about the scope of Missile Operations' various missile contracts, and provides some details on the specialized fields encompassed in missile engineering at Chrysler. It has been distributed to university placement offices and to local chapters of various engineering societies.

Convair-Astronautics

Convair—A Division of General Dynamics Corporation

San Diego, Calif.



New $40,000,000 Convair-Astronautics facility at San Diego

Convair's Background

CONVAIR is an outgrowth of Consolidated Aircraft Corporation, founded in 1923, and Vultee Aircraft, Inc., with which it merged in 1943. Eleven years later, Consolidated-Vultee Aircraft Corporation—Convair for short—merged with and into General Dynamics Corporation, to become the Convair Division of General Dynamics.

Today Convair is a prime producer of equipment for the Air Force, the Navy, and for commercial airlines throughout the world. Convair is also a pioneer in the field of guided missile production.

Among Convair's outstanding achievements are America's first turboprop aircraft, the Air Force XP-81; the world's largest bomber, the intercontinental Air Force B-36; the world's first supersonic bomber, the B-58; the first production supersonic jet interceptor, the Air Force F-102A; the first high-speed water-based jet fighter, the Navy XF2Y-1; the largest land-based aircraft, the Air Force XC-99 troop-and-cargo transport; and many others.

Convair, long known as a pioneer in the missile field, is now working on the development of the Atlas Intercontinental Ballistic Missile, a top priority project of the Air Force. Other current Convair projects include the F-106A supersonic interceptor; the Metropolitan 440 airliner; the new Convair 880 jet-liner; and a far-reaching study of nuclear aircraft.

Astronautics is the science of possible interplanetary space travel. There are many opportunities for young, ambitious engineers at Convair-Astronautics, San Diego, Calif., where a new $40 million facility is now being constructed. This facility will be devoted to research, development, manufacture, and preliminary testing of the Atlas Intercontinental Ballistic Missile. Nearly 7000 Convair people make up the staff of this project.

Several thousand engineers, technicians, and production personnel are now working on the Atlas project, and more are to be added before the new facility is ready for full occupancy in the fall of 1957.

Among the career opportunities now open to engineers at Convair-Astronautics are positions as electronics engineers, aerodynamics engineers, dynamics engineers, structures engineers, and flight test engineers.

If you are studying to be an aeronautical, mechanical, electrical, or civil engineer, a mathematician or physicist, Convair-Astronautics presents a challenge to your ambition and limitless opportunity for your talents. You will work with leaders in their engineering fields.

At Convair you will find full expression and a chance to further your engineering education—graduate study, tuition refund, and top-notch company lectures. General Dynamics recently announced a million-dollar grant to the University of California to assist expansion of the University's La Jolla, Calif., campus to provide for a graduate program in science and technology. Special consideration is offered to candidates for advanced degrees Salaries, personal benefits, associates, and engineering policies are unsurpassed in Convair's "engineer's" engineering department.

In addition to all the career advantages offered by Convair-Astronautics, there is the important consideration of delightful indoor-outdoor living in San Diego, where America's kindest climate permits year 'round enjoyment of countless scenic playgrounds and all kinds of outdoor sports. For detailed information, write:

Greg McMillan, Placement Director
Convair-Astronautics
Dept. 706B
San Diego, Calif.

Douglas Aircraft Company, Inc.

Douglas Missiles Engineering Department

Santa Monica, Calif.

THE Douglas Aircraft Company became active in missiles design and production in 1941. Steady growth made it necessary to separate completely missiles from aircraft in early 1956.

Active Missile Projects

Today the Air Force, Army, and Navy have contracts with Douglas for research, development and production of all types of missiles. These include: surface-to-air, air-to-air, surface-to-surface and air-to-surface, and IRBM.

To fulfill these requirements we have nine active missile projects, including the Nike Series, Sparrow, Honest John, Thor (IRBM) and others of a classified nature.

Locations

Our engineers have the responsibility of planning and conducting the flight tests, and of evaluating the results of the firings. The design and test work is accomplished at one of the following installations:

(a) Santa Monica, Calif.—The prime design facility for all missiles research, development, and production.

(b) Sacramento, Calif.—A newly established missile testing facility.

(c) Charlotte, N. C.—An Army Ordnance-owned facility producing Nike Series missiles.

(d) White Sands Proving Ground, N. Mex. In conjunction with Army Ordnance, the company maintains a field station of over 100 engineers and technicians to participate in field testing of the Nike and Honest John missiles.

(e) Naval Air Missile Test Center, Pt. Mugu, Calif. With the Navy's Bureau of Aeronautics, the company maintains a team of design engineers actively engaged in planning, conducting and evaluating the Sparrow flight test program.

(f) Patrick Air Force Base, Cocoa, Fla. in conjunction with the Air Force, the company performs missiles tests.

(g) Naval Ordnance Test Station, Inyokern, China Lake, Calif. Using the Navy Bureau of Ordnance instrumentation range, the company's engineers and technicians are engaged in testing rockets in conjunction with the U. S. Navy.

(h) Holloman Air Development Center, N. Mex. In conjunction with the U. S. Air Force, the company has established a field station of engineers and technicians to participate in field testing rockets.

(i) Edwards Air Force and Rocket Bases, Muroc, Calif. In close collaboration with the U. S. Air Force, the company has many engineers and technicians permanently assigned to flight testing of missiles as well as aircraft.

Expansion

With an enviable reputation for stability and experience, Douglas offers exceptional opportunities to engineers, scientists and mathematicians. In considering a future with Douglas, it is important to weigh these facts:

1 Douglas started missile development as far back as 1941.

2 A completely separate Missiles Division was created in February, 1956, with 700 engineers—a new organization offering greater opportunities plus the stability of a long-established parent company.

3 The growth of this Missiles Division is best exemplified by a staff of 1300 engineers as of November 1, 1956.

4 This division is equipped to handle all phases of research, development, and production.

5 Contracts have been made with various branches of the Army, Air Force and Navy.

6 Already, nine separate missile projects are affording unlimited personal opportunities.

Even though our expansion has been great, it must continue at an even greater pace if we are to fill the senior openings created by our customer commitments. It is our intention to continue to be selective so that our team of engineers and scientists will be able to produce a product worthy of the Douglas name.

Technical Opportunities

Today there are senior openings in each of our Technical Sections. Here is a complete list of these sections along with a brief résumé of their functions:

Advance Design. Preparation of preliminary data and establishment of design concepts for new or modified missiles and for complete missiles systems.

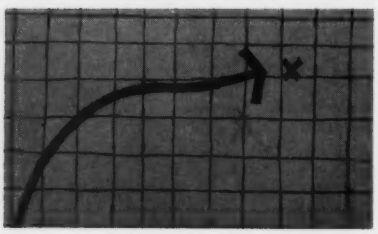
Aerodynamics. Development of the most effective and practicable design for each proposed or current missile or weapons system, with respect to aerodynamics, flight mechanics, ballistics and flight characteristics.

Sparrow—Air-to-air

Automatic Controls. Analysis of requirements for and design of dynamic systems related to the guidance, control, and fire control of missiles, as well as to the delineation of the characteristics of equipment required for these purposes.

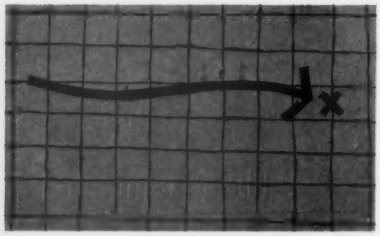
Check (Drawing). Checking of engineering drawings to assure that design intent has been correctly portrayed and is

Surface-to-air



Air-to-surface

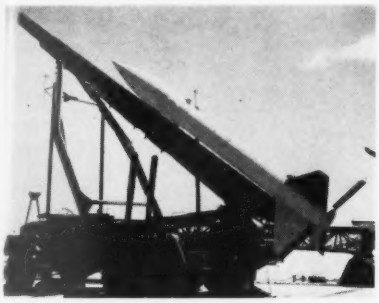
Air-to-air



consistent with customer requirements and the policies of the DAC Missiles Engineering Department.

Computing. Solution of engineering problems by computing engineers through technical consultation, programming, and machine operation on the most modern equipment available.

Data Reduction. Assembly of raw test data from all available sources; the efficient reduction of these data to forms suitable for engineering analysis and evaluation; and the preparation and distribution of preliminary data reduction reports.



Honest John—Surface-to-surface

Equipment. Design and development of electrical and electronic equipment and installations for missiles systems and the preparation of necessary drawings and other engineering data required for the production of such equipment and installations.

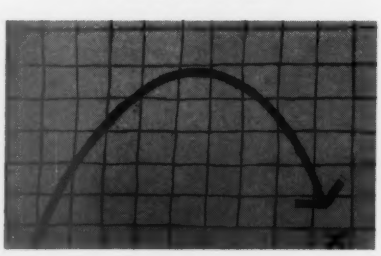
Ground Equipment. Design and development of ground support equipment and installation including handling and launching equipment, site arrangement, trailers, vans, test equipment, assembly and maintenance equipment, packaging, plus training aids and special devices.

Hydro-Mechanical. Design and development of hydraulic and pneumatic systems, armament systems and temperature control equipment, together with necessary components, parts, and installation requirements for these systems in missile production.

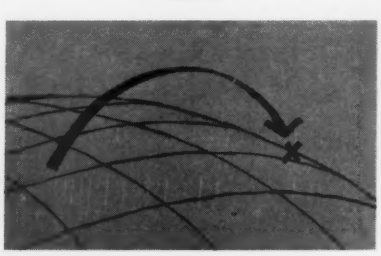
Power Plant. Design and development of power plant components and accessory components—together with assembly and installation design—for use in new design concepts and modified versions of missiles and rockets.

Reliability. Determination of the reliability of missiles and missiles systems, analysis of the causes of low reliability and assistance to designers—where possible—in devising methods and procedures for obtaining the required reliability.

Surface-to-surface



IRBM



Nike—Surface-to-air

Research. Conduct of research of problems in the field of missiles, aircraft and space craft; and exploration of the realm of new tasks, new techniques and new technologies which may enhance and broaden the performance, operation and usefulness of such vehicles.

Strength. Provision of adequate strength, rigidity, and freedom from detrimental dynamic effects for missiles and their supporting equipment. Establishment of design criteria in conformity with military requirements to serve as a basis for the structural design of each model.

Structures. Design and development of structural components including the initiation of new design and modifications which improve fabrication, assembly or installation of structural components. Also design research on applications of new processes and materials.

Thermodynamics. Analysis of all missile heat transfer problems including aerothermodynamic heating, equipment conditioning and internal temperature gradients affecting structures.

Weights. Determination that the design effort of all sections will result in the lightest missile components consistent with engineering policy and military characteristics.

Your Future

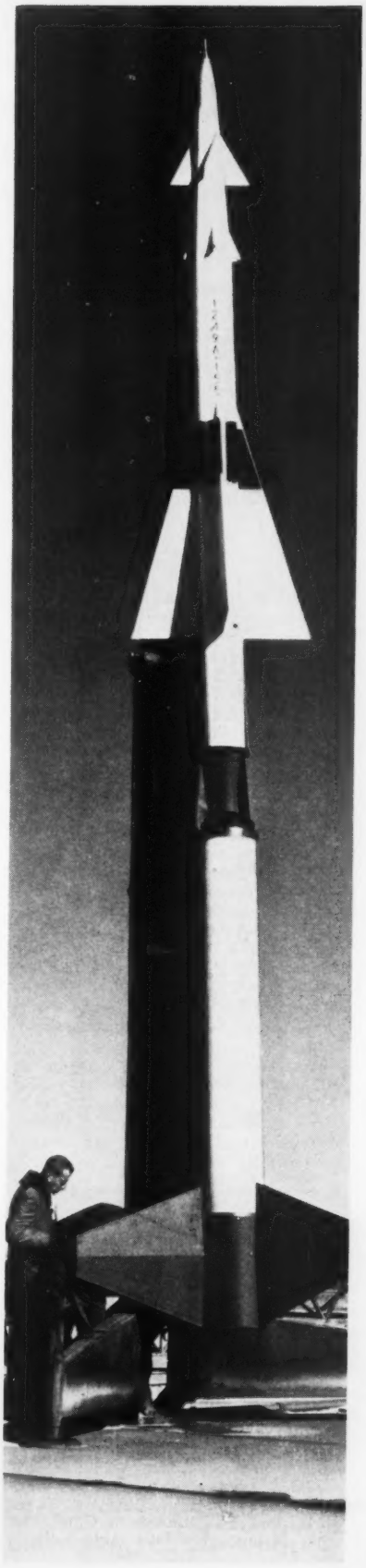
Most of the top men at Douglas are engineers who came up through the engineering ranks—such as D. W. Douglas, Sr., President and Chairman of the Board; F. W. Conant, Senior Vice-President; D. W. Douglas, Jr., Vice-President, Military Relations; A. E. Raymond, Vice-President, Engineering; and E. P. Wheaton, Chief Missiles Engineer.

Years ago, Douglas recognized that professional problems are best resolved by professional men. For this reason our facilities, our pay scale, our educational programs and advancement programs are geared to professional needs.

Contact

If you are an engineer or scientist, if you are studying along these lines or if you have qualifications that would be of value in the Douglas missiles program, you are invited to contact:

Mr. E. C. Kaliher, A-260
Missiles Engineering Personnel Manager
P. O. Box 620-RM
Douglas Aircraft Company, Inc.
3000 Ocean Park Blvd.
Santa Monica, Calif.



Cornell Aeronautical Laboratory, Inc.

of Cornell University

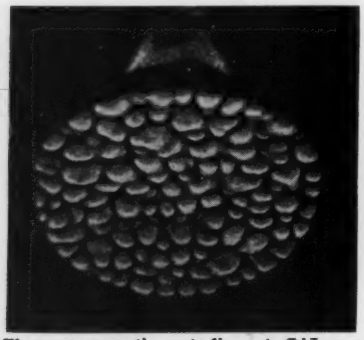
Buffalo 21, N. Y.

Scope

CORNELL Aeronautical Laboratory is a not-for-profit organization of approximately 1200 people of whom 400 are engineers and scientists. Primary emphasis is placed on applied research, complemented by pure research and development. Major Laboratory effort is currently focused on guided missile technology, systems evaluation, operational analysis, and design studies.

CAL's work in combustion and propulsion dates back to the founding of the Laboratory. Under the Navy's Bumblebee program, CAL conducted the first known demonstration of the validity of the ramjet concept in a small air jet at supersonic speeds, and proved the feasibility of jet vane control. The most recent "printable" accomplishment of the Laboratory in these fields is the Lacrosse missile. CAL has been responsible for the entire missile system, including airframe, guidance, propulsion, and launching equipment.

CAL has recently begun work on the development of a device to permit testing of airborne vehicles at speeds in excess of 10,000 mph, and temperatures of 9000 F for time periods far greater than ever before possible.



Flame propagation studies at CAL revealed that in certain mixtures the flame front disintegrates into fairly uniform cells.

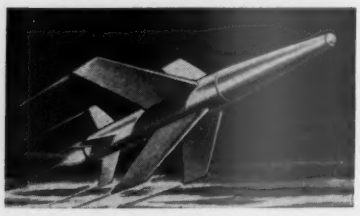
Opportunities

CAL research is not limited to any product, but covers a wide variety of fields. For example:

- Combustion and propulsion
- Thermodynamics
- Heat transfer
- Environmental and field testing
- Gasdynamics
- Computer design
- High temperature studies
- Missile design
- Wind tunnel research (subsonic through hypersonic)
- Missile trajectory studies
- Weapon systems analysis
- Guidance techniques

Careful selection of personnel and equal selectivity in project choice combine to insure a program that is both significant and technically stimulating.

Nighttime test of application of valveless pulsejet to helicopter drive.



The Lacrosse missile—created for the U. S. Army by CAL. The mobility and accuracy of this system will provide close support for infantry operations.

Salaries and Benefits

Engineering salaries at CAL are very similar to those normally associated with the more progressive aircraft companies. Five-digit salaries are not uncommon. Equal financial and status rewards are provided for advancement of both supervisory and technical personnel. Benefits include medical program, retirement plan, credit union, group insurance, paid vacations, and tangible support for those interested in advanced education.

Locale

Buffalo, N. Y., offers a stable, year 'round climate, a vast array of cultural and recreational activities. Its metropolitan area totals over a million people. It has 10 parks, beautiful residential sections, excellent schools, and chapters of all major technical societies. Buffalo is just a bridge-length from Canada, a sportsman's paradise, and less than 20 miles from Niagara Falls. It offers American League hockey, International League baseball, and many collegiate spectator sports. Located on Lake Erie, the City of Good Neighbors abounds with opportunities for golf, boating, skiing, hunting, fishing, and all participant sports.

Write for Free Booklet

"A Community of Science"—a factual, well-illustrated description of the Laboratory and its research program—plus pertinent information on such subjects as salaries, benefits, and educational programs.

Address inquiries to G. Moison, Cornell Aeronautical Laboratory, Inc., 4455 Genesee St., Buffalo 21, N. Y.

Fairchild Engine Division

A Division of Fairchild Engine and Airplane Corporation

Deer Park, Long Island, N. Y.

FAIRCHILD Engine Division at Deer Park, Long Island, N. Y., is one of the nation's leading producers of jet engines and jet engine components, and pioneer in research, development, and production of small, lightweight jet engines.

Its range of activities includes power plants for inhabited and uninhabited aircraft; major components for jet engines; and underwater weapons such as the U. S. Navy's new X-1 midget submarine.

An extensive new facility at Deer Park has recently gone into operation. It comprises a new plant and a Gas Turbine Laboratory providing those in advanced engine research and development with the most modern equipment available. Present projects involve new small jet engines for many applications; radical new propulsion systems, fuels, designs, etc., for use by both the Armed Forces and the commercial aviation industry.

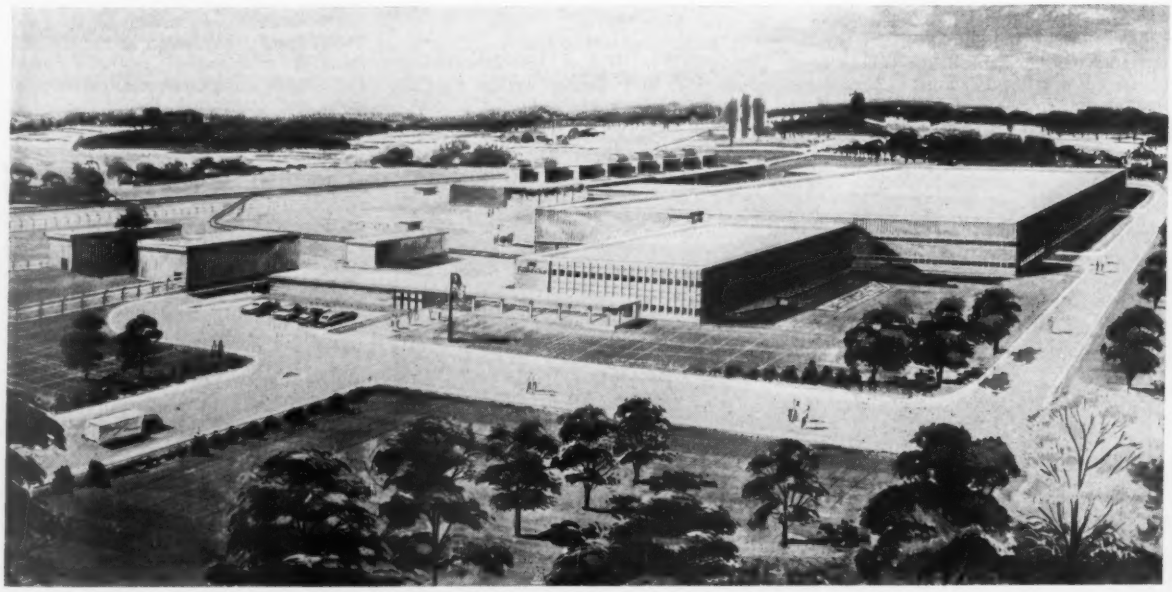
These expanding programs insure more than just the basic opportunites for both the young and the experienced engineer. And the company's approximately 30 years of constant progress in all phases of power plant development and manufacturing are reflected in its modern personnel policies and practices, which include many well-directed programs such as internal training and orientation, and ample opportunity for educational progression.

Liberal noncontributory pension plans as well as better-than-average health and life insurance benefits are provided. Most important, Fairchild Engine Division applies its policies and benefits to insure each employee personal attention.

New Fairchild Gas Turbine Laboratory incorporates the latest and most advanced equipment

Living conditions in Long Island are excellent. Low-cost attractive housing is available; good schools, hospitals, and shopping centers are conveniently located.

Metropolitan New York is close by and virtually every sort of recreational facility is readily available—golfing, swimming, fishing, boating, riding.



Fairchild Engine Division's new home for power at Deer Park, Long Island

Ford Instrument Company

Division of Sperry Rand Corporation

31-10 Thomson Avenue, Long Island City, N. Y.

Missile Guidance

FORD Instrument Company has spent quite a number of years working on missile guidance systems for the Air Force, the Navy, and the Army. These have ranged from launching systems to inertial guidance systems and include projects which cannot be discussed because of security restrictions. Among the major missiles FICo is working on are the Terrier and Tartar missiles for the Navy and the Redstone and Jupiter missiles for the Army Ballistic Missile Agency. These top-priority programs will require considerable expansion in many types of personnel and facilities. For that reason the company has established a new Missile Development Division.

Expanding Facilities

A third building has been acquired to provide a place for the engineering development, experimental, and test facilities for the ballistic missile work of the company. To further increase the company's research, design, and manufacturing facilities, a new gyroscope test laboratory has been built with the most modern equipment available for this work, and a new microwave laboratory has been added. Extensive environmental laboratories have been established to enable the equipment developed at Ford to meet the rigorous requirements of military specifications.

Company Growth

Ford Instrument Company was founded in 1915 by the late Hannibal C. Ford, to develop, design, and build computers and controls for naval guns. Mr. Ford's inventions revolutionized naval warfare by introducing what is now called "automation" into ship gunfire control. As time went on, the company developed the first automatic computing antiaircraft gun director and a whole group of surface-fire computers, gun drives, torpedo guidance systems, and their related components.

In more recent years, Ford has been a leading company in the development of aircraft navigational systems, cruise control instruments for jet aircraft, various accurate timing devices, weapon control systems, and missile and rocket launching computers. It is under contract to the Army, the Navy, and the Air Force for many instruments which, due to their classified nature, cannot be discussed.

The instrumentation and controls for the atomic submarine, "Seawolf," were developed and built at Ford Instrument Company, and the engineers at Ford are currently busy on contracts with the AEC and have designed reactors for both a municipal power plant and a power plant of an ocean-going tanker.

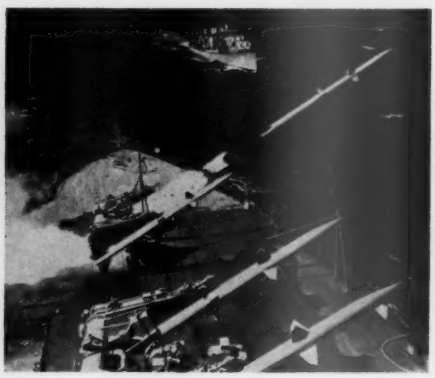
It is but natural that a company so experienced in precision equipment, control, computing, and sensing devices should enter the missile guidance field. Its work with the engineers at the Redstone Arsenal for the past number of years has enabled Ford to become one of the most experienced companies in the country on ballistic missile guidance systems.

The company is a division of the great Sperry Rand Corporation, one of the outstanding organizations in the world in the field of computers, electronics, controls, and other such highly engineered equipment.

Only eight years out of engineering school, Lewis Scheuer has risen to the newly created position of Director of Engineering of the Missile Development Division.

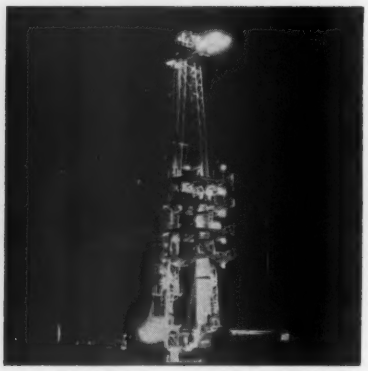
U. S. Navy Photograph

Shore bombardment rockets being fired from the USS Carronade. Ford computers aim these missiles.



U. S. Navy Photograph

Terrier missiles being fired from a warship. Ford developed the launching computers for this A.A. weapon.



U. S. Army Photograph

A Redstone ballistic missile being prepared for launching—Ford engineers helped develop the guidance system.

Opportunities at Ford

With the formation of the new Missile Development Division, a great many opportunities are opened for capable engineers. The program of enlarging this department steadily during the next several years will give engineers an opportunity to advance with the growth of the new division.

The company has an enviable record. Since its founding in 1915, Ford Instrument Company has never terminated a competent development engineer because of lack of work, and we will continue to maintain this record.

Our company has always promoted from within. Our president and our chief engineer as well as other top executives started their careers as engineers with the company. This promotion policy shows a ready recognition of ability and initiative.

Engineers find that work with Ford Instrument Company offers many advantages. Working in small teams on specific projects allows each man to increase his personal knowledge as he works closely with the other engineers and participates in conferences on over-all problems with specialists in various fields. He also is in a position to receive personal recognition for his own work.

There is the additional satisfaction of seeing the work he is doing through from initial theory to finished product.

The company employs about 2700 people of whom 525 are research, development, test, and production engineers.

Engineers Needed

At present the new Missile Development Division is looking for electrical engineers, mechanical engineers, test engineers, and field service engineers, in the research and development as well as the production and product engineering phase.

Bachelors, Masters, and Doctors in engineering or men whose background, training, and work experience would qualify them for the work being done are being sought. Applicants must have an interest in and capabilities for research and development, for learning new techniques and skills, for advancing with the future advances made in control engineering.

Salaries are commensurate with a man's education, experience, and abilities, and are reviewed every three months to determine whether a man may be raised to a higher salary or to a higher job classification.

Most of the work will be done at the home plant of the company. However, after an indoctrination period, a number of engineers and field service personnel will be assigned to the company's laboratories at the Redstone Arsenal in Huntsville, Ala., and some will go to Patrick Air Force Base test center in Florida.

Benefits

In addition to the regular salaries, Ford provides for the financial security of its employees and their families in many other ways, amounting to more than 25 per cent over the quoted salary. The company pays three quarters of the Accident and Sickness Insurance and the entire expense of: Retirement Pension Plan; Sick Leave Pay; Hospitalization; Surgical Benefits (40 per cent over Standard Blue Shield); In-Hospital Medical Benefits (50 per cent over standard); Group Life and Disability Insurance; nine full and two half-day holidays and two weeks' vacation (after 10 months' employment). Besides these, the company has thorough free health examinations for all employees who desire them, and the company will refund the cost of tuition for any advanced courses of study and one half the membership dues for one engineering or scientific society.

The plant location within fifteen minutes of the heart of New York City allows its employees many benefits. Not only are there fourteen colleges and universities in the area (for an engineer or his family to attend) but also theaters, music, sports, museums, and other attractions of America's Number One city readily available. Within a few hours the boating, swimming, and fishing of the Atlantic coast, the golf, tennis, skiing, and hunting of New England and Long Island can be reached. Most of our employees live with their families in the suburban fringes of the city.

Other Opportunities

Besides the work to be done by the new Missile Development Division at Ford Instrument Company and which is a program extending many years into the future, there are many other activities in the plant which offer opportunities to engineers and physicists.

Other missile guidance programs besides that of ballistic missiles are being worked upon also. Ford developed and built the launching computer for the Terrier missile as installed on the USS Boston and Canberra. Special projects demanding talents in servomechanisms, data processing design, gunfire control, and aircraft instrumentation call for additional engineers now and in the future.

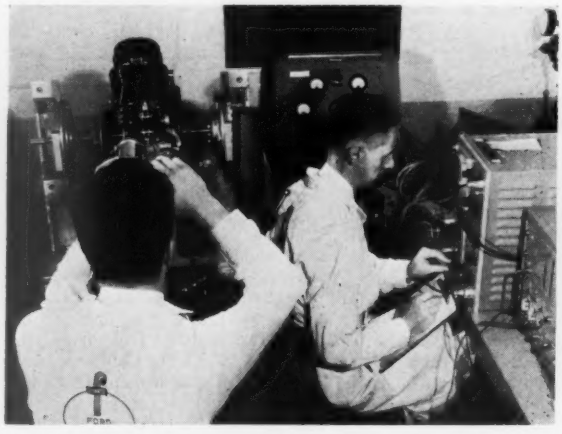
Nuclear reactor contracts have called for additional men with experience in that field, and there are a number of positions for radar specialists.

Increasingly strict environmental conditions for equipment used in this supersonic age call for the design of special test equipment, the ability to direct elaborate shock, acceleration, temperature, and other tests of all components and systems. Engineering writers capable of preparing engineering reports, operation and maintenance manuals or instruction courses also have a future at Ford.

Due to the nature of the company's work, all engineers must be able within a reasonable time to obtain and retain a security clearance required to work on military equipment.

Write in Today

If you are interested in a career in the field of missile guidance or in weapon control work—if you feel that your abilities and training qualify you for this work, write to Philip F. McCaffrey at the Ford Instrument Company, Division of Sperry Rand Corporation, 31-10 Thomson Avenue, Long Island City 1, N. Y. He will send you all information and let you know how an interview may be arranged. There is a future for capable engineers at Ford Instrument Company. You may find your successful future there.



Ford Instrument Company engineers measuring drift rate of gyros through an auto-collimator and checking magnetic amplifier components for a missile guidance system.

Checking voltage and frequency accuracy of a power supply unit under simulated load conditions for a guidance system being developed for the Army Ballistic Missile Agency.

Firestone Tire and Rubber Company

Guided Missile Division

2525 Firestone Blvd., Los Angeles 54, Calif.

Organization

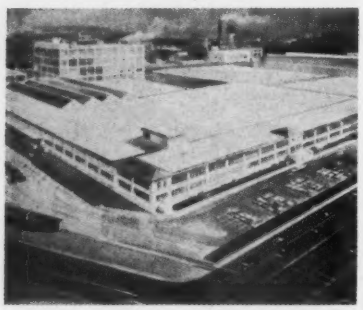
THE Firestone Tire and Rubber Company for many years has held a position of leadership in weapons research and manufacture. Engineering and production achievements at Firestone's defense products facilities have included 90-mm tank cannon, 3-in. 0.50-caliber naval guns, 40-mm antiaircraft batteries, 106-mm recoilless artillery weapons, and troop-carrying gliders.

In its Los Angeles facility, Firestone is carrying forward the vital development and production program for the first operational ballistic missile, Corporal. More recently, the firm has opened a new engineering laboratory at Monterey, California, for research and development work on weapons systems, providing ground-floor opportunities for qualified men to work with a select team of advanced researchers.

In its never-ending program to improve both the performance and producibility of the Corporal, and in its growing Monterey research efforts, Firestone offers unexcelled challenges to stir the imagination of high-calibre engineers and scientists.

Guided Missile Division activities are supported by the financial and managerial resources of the entire Firestone organization, a leader in American industry and research since its founding in 1900.

The Guided Missile Division provides complete facilities for the development, engineering, fabrication, and evaluation of prototypes, and the production of resultant designs.



A new multimillion-dollar facility in Los Angeles was constructed in 1955 to house the Guided Missile Division

Activities

Unlimited opportunity exists in the Guided Missile Division for engineers and recent engineering graduates. The professional development of each engineer is encouraged at Firestone, and is limited only by the capability of the individual to learn and by his ability to utilize his basic engineering education.

Projects now under way in the Guided Missile Division include studies in flight simulation, environmental and flight testing of missile components, and the design of automatic rest consoles for electronic equipment. Engineering effort is being expended on all phases of electronic component and circuit design, miniaturization processes, and in techniques of missile guidance. Studies are being conducted in automation and in computer research.

Engineers in the Guided Missile Division have challenging responsibility in many new developmental projects

In addition, electronic studies are under way in theoretical and applied systems, design of special test equipment, and systems analyses.

Engineers in the mechanical engineering sections are concerned with design, in providing reliable hardware and documents, and insuring economic production for the Corporal system. Structures, ground support equipment, propulsion, materials, and prototyping are included among the many projects conducted in this engineering phase. Involved fields include stress analysis, hydraulics, pneumatics, metallurgy, and plastics research.

Broad technical and laboratory facilities are the keynote of an aggressive research organization, and at Firestone these facilities are exemplary.

Training

Firestone engineer-trainees receive comprehensive instruction in all phases of missile characteristics

Integrated training programs for professional and managerial advancement are a vital part of the Guided Missile Division's engineering effort. From the day each new engineer joins Firestone, he is given orientation by, and works with, qualified and experienced engineers.

Firestone's comprehensive engineering training program for recent college graduates includes extensive classroom training followed by rotating assignments within the division. Classroom work, in combining lecture courses on the electronic and mechanical characteristics of missile systems with practical demonstrations of these principles, aids in preparing the young engineer for the diversity of assignments he may be given in the engineering department.

In the on-the-job phase of Firestone training, the engineering trainee is guided by experienced engineers and is given responsible assignments as soon as possible compatible with the degree of problem complexity and the capabilities of the individual. This training plan is designed to provide each engineer with an assignment, after training, in which he can best utilize his talents and his capabilities.

Academic training also is available through the Guided Missile Division. Located in the Los Angeles area are the California Institute of Technology, the University of Southern California, and the University of California at Los Angeles; Firestone's employee advancement program provides for tuition reimbursement to employees successfully completing university and college courses during their employment.

Grand Central Rocket Co.

Box 111, Redlands, Calif.

One of Grand Central Rocket Company's important programs in 1956 was the design, development, and testing of the 18,000 mph solid propellant rocket motor for the third stage of the Earth Satellite Project Vanguard.

A MAN'S future must be respected second only to his life. His future is his life.

Choosing that future wisely is the difference between success and failure, between content and dissatisfaction, between exciting challenging work and dull routine.

Men grow as their futures grow. Very few humans come into this world with a premium brand of genius. The dependable minds begin at the bottom and evolve with experience to the top.

When you select an employer whose magnitude requires thousands of men, your chances for rapid promotion diminish. With an employer whose expansions are ahead of him, rather than behind him, your chances for rapid promotion mathematically increase.

That is what the Grand Central Rocket Company offers; that, plus an exciting and challenging career in the amazing and youthful field of solid propellant rocket motor development.

Last year at this time and in these pages we extended an invitation to young engineering, technical, and business administration talent. We employed nearly 100 of them. While they were on salaries comparable with any paid by other companies, they began intensive training. There was direct work-training at the plant. There were academic courses at the University of Redlands, nearby us. Our motive was to develop business administrators and project engineers—rapidly. Most of these men are in responsible positions today—less than a year after being employed.

Their work has been anything but dreary. They have been working on some of the most fabulous rocket projects in history: The supersonic Wasp, the Asp, the Dart, the hypersonic HTV, and the incredible 18,000 mph solid propellant rocket motor for the third stage of Earth Satellite Project Vanguard, just to mention a few. Today these men are probing their way into the frontiers of space with long-range missiles and satellites. Their future is as open as space and as sound as the earth.

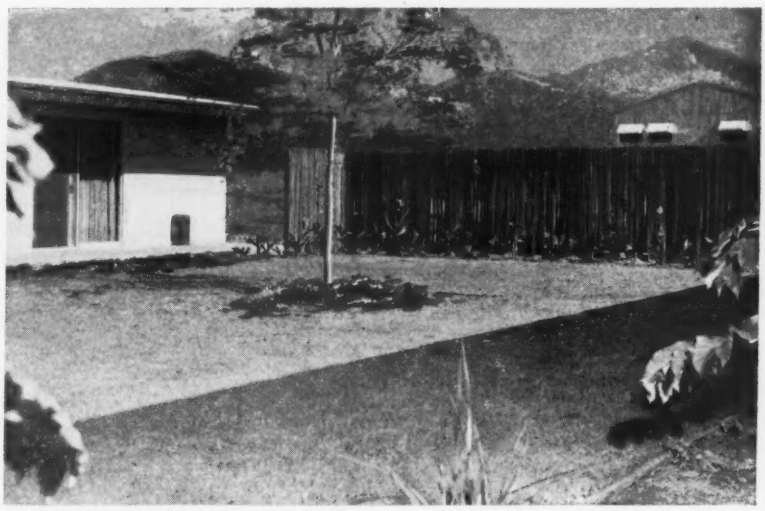
At Grand Central, only three specific attributes are required: Ability, initiative, and the willingness to accept responsibility.

We regard our company as a team—a team of scientists, engineers, production, and business administration experts; a team that is nationally recognized as pioneers and leaders in applied research, development, and production of solid propellant power plants for all types of rocket applications.

We like to look upon ourselves as a small but vital company. Actually, we are not so small. At the moment we are operating on a 1000-acre property with some 28 different facilities and we will be compelled to expand again this year.

Our people are singularly happy with our geographical location, for several reasons. The plant is in a smog-free citrus area on the outskirts of Redlands, in southern California. Redlands is a beautiful residential and university town of about 20,000. It is 65 miles east of Los Angeles over a fine high-speed freeway. A one-hour's drive will get you into the ski runs, the desert flowers, or in an hour and a half you may swim or fish in the Pacific Ocean.

We are looking for more men to look into space with us. The opportunity for an interesting future is here for mechanical, structural, chemical, aeronautical, industrial and civil engineers; to mathematicians, physicists, technical writers, illustrators, and business administration careerists. When choosing your future, offer your qualifications to: Personnel Director, Grand Central Rocket Co., P. O. Box 111, Redlands, Calif.



Grand Central's facilities nestle among golden orange groves at the foot of a great mountain range three miles from the university town of Redlands, Calif. Shown here is one of the landscaped Administration Building patios.

Martin

Baltimore 3, Md. ***Denver 1, Colo.***

MARTIN, the pioneer in upper air research with the Viking rockets and leader in tactical missile design with the Martin Matador, has current projects of vital importance under way. Martin is the prime contractor for the first earth-circling satellite—Vanguard—to be launched during the International Geophysical Year, July 1957–December 1958. This vehicle will furnish hitherto unattainable scientific information on the upper atmosphere.

Martin is also working on an Inter-Continental Ballistic Missile—Titan. Work on the Titan is going forward with the highest military priority in Martin's new plant in Denver. Design details on this weapon are still under strict security wraps.

To engineers, Martin's leadership in rocket and missile design means present opportunity for an unlimited future. The Vanguard, Titan, Viking, and Matador programs are indisputable earners of that leadership. Martin has a present and continuing need for the far-sighted engineer—especially in these fields: Aerodynamics and Propulsion (Ballistics, Heat Transfer, Gas Dynamics, Propellants, Combustion, Fluid Flow); Flight Path Control (Guidance, Controls, Computers, Tracking); Structures (Extreme Temperature Materials, Environmental Vibration and Shock); Product Design (Airframe, Equipment Integration, Support Systems); Testing (Instrumentation, Data Processing, Telemetering, Flight Testing); Upper Atmosphere Research (Ionosphere, Meteorology, Gravity, Cosmic and Solar Radiation, Density, Pressure, Temperature).

Contact:

J. J. Holley
Martin
Baltimore 3, Maryland

Emmett E. Hearn
P. O. Box 179
Denver 1, Colorado

McDonnell Aircraft Corporation

Missile Engineering Division

Box 516, St. Louis 3, Mo.

ENGINEERS and scientists of the McDonnell Missile Engineering Division enjoy the pleasant, creative environment engendered by our new "Engineering Campus." Because of its rapid growth, the Missile Engineering Division has occupied the first completed building located on the left in the above architect's illustration of these new facilities. All of our engineering divisions will occupy these buildings by mid-1957.

The Missile Engineering Division of McDonnell is dedicated to the conception, design, and production of new missile weapons and missile systems. In past years, McDonnell has made many valuable contributions in this field; the company's activities have included remotely controlled target drones as well as missiles of practically every category. The success of McDonnell in these varied enterprises is reflected by the rapid growth of the Missile Engineering Division. In a relatively short span of time, it has grown from a small group to its present place as one of McDonnell's three major divisions, the other two being Airplane and Helicopter.

McDonnell currently is working on the development and production, under firm contracts, for three separate and distinct categories of missiles which include air-to-air, surface-to-surface, and surface-to-air weapons systems. In the interests of national defense, these are naturally highly classified; however, the ramjet-powered Talos surface-to-air missile has been publicly announced as one of the Navy's prime air-defense weapons.

The problems of guided missile development are so varied that all types of engineers can be utilized in their solution. The Missile Engineering Division offers stimulating assignments to: Aeronautical, Mechanical, Electrical, Electronic, and Civil Engineers, in addition to men with Engineering Physics or Applied Math degrees.

Two excellent schools, St. Louis University and Washington University, are conveniently located in the local area. McDonnell will assist qualified individuals holding a full undergraduate degree to undertake studies leading to a Master of Science or Doctor of Science degree. Similar assistance is also given those interested only in a few specialized courses that will assist them in their particular assignment.

The McDonnell plant is located eleven miles northwest of St. Louis where you can enjoy the ideal combination of suburban living with access to big city attractions. Alton Lake, north of St. Louis, and the beautiful Lake of the Ozarks, in mid-Missouri, are available for weekend recreational activities.

Present-day missiles which fly at supersonic speeds, and proposed designs which reach out into the hypersonic ranges, involve aerodynamic, thermodynamic, and structural hypotheses by which the future development of air transportation may well be governed.

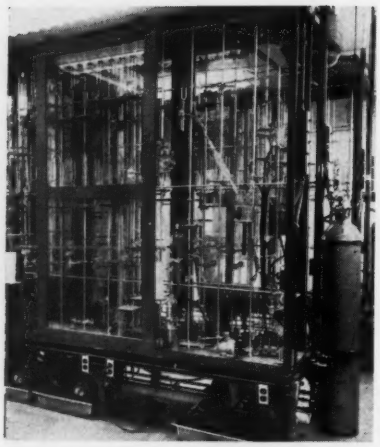
This may be your opportunity to join our Missile Division and help make missile history. For additional information, write today for our engineering brochure to:

R. F. Kaletta
Technical Placement Supervisor
P. O. Box 516
St. Louis 3, Mo.

Olin Mathieson Chemical Corporation

Explosives Division

East Alton, Illinois



FROM THE LABORATORY—where the most advanced of equipment and techniques are coupled with creative ingenuity

The Division

THE Explosives Division of the Olin Mathieson Chemical Corporation traces its history back to 1892 when founded by F. W. Olin. Throughout its history the men in this Division have been aggressive in the development of new propellant and explosive materials. Today many of the foremost products in this field stand as a credit to their creative efforts.

In the propellant field Ball Powder, a smokeless powder prepared by a revolutionary new process, has gained wide acceptance as a superior product for small arms and aircraft weapons. Similarly, an economic new process has been developed for production of double base solid rocket propellants. And the manufacture of jet engine starter cartridges has been successfully reduced to simple production practice.

Today new composite propellant developments are demanding the utmost in creative skills. The Explosives Division, both independently and in conjunction with other components of the Olin Mathieson Chemical Corporation, is working on major programs to establish higher impulse propellant systems.

Thus from low energy formulations to high energy systems, from slow burning to rapid burning compositions, the Olin Mathieson scientific team is pioneering, reducing today's theory to tomorrow's practice. Old in tradition, new in ideas, this is a group offering a rich training and opportunity for the young engineer or scientist.

The Company

The Olin Mathieson Chemical Corporation today ranks as one of the nation's principal diversified industries with plants in 27 states and 17 foreign countries. The company enjoys an international reputation not only as a processer of large tonnages of raw materials of the useful industrial chemicals but also as a producer of explosives, propellants, ordnance items, and other materials of interest to both the military and commercial users.

In support of these production activities as they exist today and are planned for tomorrow is an engineering and scientific staff of more than 2000 people. And one of the most prominent areas of present expansion within the broad scope of corporation endeavor is that of aircraft and missile propulsion.

THROUGH TESTING—where progress is measured and problems are redefined

The Locations

Principal research and development facilities in the solid propellants field are at our plants at Ordill and East Alton, Illinois.

East Alton is located approximately 25 miles north of the heart of St. Louis, affording ready access to the educational and cultural opportunities of this metropolitan area, and at the same time offering a choice of living in a variety of urban or rural communities. The new Ordill plant is located in southern Illinois adjacent to the Crab Orchard Wild Life and Game Preserve and the Southern Illinois University campus, presenting unique opportunities for the sportsman as well as the student.

A Future with OMCC

Opportunities exist at the present time in:

- Fundamental research in high energy fuels and new explosives
- Applications engineering of high performance rockets, APU's, and ejection devices
- Process development of propellant formulations including pilot plant and semiworks operation
- Propellant and rocket manufacture, quality control, and testing
- Theoretical and practical studies on combustion ignitions and detonation

For work in these fields, you may qualify if you have training in:

- Chemistry
- Physics
- Mathematics
- Mechanical engineering
- Chemical engineering

Our research and development program is conducted through a project engineering system, i.e., the assignment to individual professional personnel of project task assignments commensurate with their experience and training. Thus each man both works closely with others and at the same time has the opportunity for independent action, for rapid progress, and for individual accomplishment.

Those wishing to obtain further information concerning the opportunities for a professional career with the OMCC Explosives Division, can do so by contacting Director of Research, Explosives Division, Olin Mathieson Chemical Corporation, East Alton, Illinois.

TO PRODUCTION—where the results of development efforts are translated to useful propellant grain manufacture

Pan American World Airways, Inc.

Guided Missiles Range Division

Patrick Air Force Base, Fla.

PAN AMERICAN World Airways is the first airline engaged in the field of guided missile activity.

Scope

Pan American's Guided Missiles Range Division was created in 1953 for the purpose of managing, operating, and maintaining the complex 5000-mile Air Force Missile Test Range. It provides support for flight tests and data collection and analysis for all missiles tested at the missile test range. This support has made possible operational research projects resulting in the development of the Martin Matador, Northrop Snark, Army Redstone, Boeing Bomarc, and other missiles. Future plans include support of the launching of the first Earth Satellite Vehicle as part of the United States' participation in the International Geophysical Year activities.

Field of Activities

To direct these operations, specialists in the fields of electrical, mechanical, civil, and administrative engineering planning are needed.

Electronic engineers specializing in radar will be given work with precision tracking and search radar, and CW trajectory measurement equipment. Telemetry, timing, and digital and analog computer specialists are also needed.

Communication engineers are active in the fields of radio communications, teletype, telephone, and microwave systems.

Electrical engineers will design construction of power plants, power distribution systems, substations, and general electrical work.

Mechanical engineers will design fuel transfers as well as LOX and high-pressure piping systems.

Civil engineers design and modify structures, roads and grounds, docks, launch stands, and other support facilities.

Administrative engineers perform liaison between PAA, the Air Force, and Missile contractors.

On-the-Job Training

A select group of young men with engineering degrees will be given on-the-job training by specialists in various fields. These trainees will have the advantages of working with a wide range of missile support activities before selecting their specific field of specialization. In addition, PAA's policy of promotion from the ranks offers a definite future for the man who knows the operation.

Benefits

The complete benefit program offered by PAA includes paid vacations and sick leave, pension and group life insurance, merchandise discounts, recreational activities, and a credit union.

Flight discounts are available on many leading domestic airlines. A 90 per cent vacation discount on PAA flights is awarded employees at the end of one year's service.

A Choice Location

Centrally located on Florida's east coast, midway between Melbourne and Cocoa, PAA employees enjoy the advantages of suburban living and tropical climate. Excellent hunting grounds, fresh and salt water fishing, beautiful beaches, and a vast variety of outdoor activities have made this area one of the nation's favorite tourist centers. The famous cities of Orlando, Daytona Beach, and Miami are within easy driving distance for those who enjoy urban atmosphere.

Interviews Arranged

For a personal interview leading to an entirely different type of guided missile career, please write, sending résumé of your qualifications and experience, to:

E. A. Anderson
Employment Superintendent
Pan American World Airlines, Inc.
Guided Missiles Range Division
Patrick Air Force Base, Fla.

The AFMTC missile test range is 5000 miles long

Ultramodern Technical Laboratory, Engineering Center

Phillips Petroleum Company

Bartlesville, Oklahoma

FROM the test tube to the successful firing of a variety of solid propellant rockets, including the world's highest thrust single rocket motor all within a five-year period is—in brief—the early history of significant achievements in rocketry by Phillips Petroleum Company. Phillips scientists and engineers have developed a family of solid rocket propellants manufactured from readily available petroleum raw materials, of which the company is a major supplier.

The Rocket Fuels Division of Phillips Petroleum Company is Contractor-Operator of Air Force Plant 66, a multi-million dollar plant located in central Texas. Air Force Plant 66 is a completely modern government-owned facility, providing extensive facilities for applied research, development, test, and manufacture of solid propellant rockets. Air Force Plant 66 is a 12,000-acre reservation with adequate space for expansion of present facilities and for addition of new facilities.

Far-sighted planning and keeping abreast of current developments in the field of rocketry by Phillips Petroleum Company's team of scientists and engineers brought about the development of the M15 JATO, a new type of smokeless jet-assist take-off rocket.

The Phillips M15 JATO, as it is designated by the Air Force, utilizes such petroleum products as synthetic rubber, carbon black, and ammonium nitrate. It is the first of its type in the United States to fully qualify for production under the Air Force's most stringent performance requirements.

In addition to the M15 JATO, Phillips scientists and engineers have developed a family of rocket propellants for missile boosters much larger in size and more powerful than the M15. Included in this family of "king size" rockets is the Pusher, one of the series of booster-type rockets successfully designed, developed, and test-fired at Air Force Plant 66. Pusher is a rocket of the family that yields high thrust for short durations. In addition to the Pusher rocket, this family includes the rocket producing the world's highest known thrust, for a single solid propellant rocket motor, as well as a rocket which produces the longest duration ever achieved by large solid propellant rockets.

Air Force Plant 66 provides extensive facilities for undertaking almost any type of program in the solid propellant rocket development field. Development facilities include a well-equipped laboratory for bench-scale experimentation, a completely integrated pilot plant for full-scale development studies, and a pilot line for comprehensive studies of manufacturing techniques and small production program. Test facilities include a completely instrumented proving ground for static and environmental testing of rocket engines up to 1,000,000-lb thrust. The modern, flexible manufacturing line at Air Force Plant 66 is capable of producing solid propellant rockets in a variety of sizes.

Exceptional opportunities and challenging positions await those interested in the various phases of research and development relating to the rapidly expanding rocket field. Employment at Rocket Fuels Division offers rewarding experience to young engineers or scientists, as well as exceptional and diversified challenges to the man of experience.

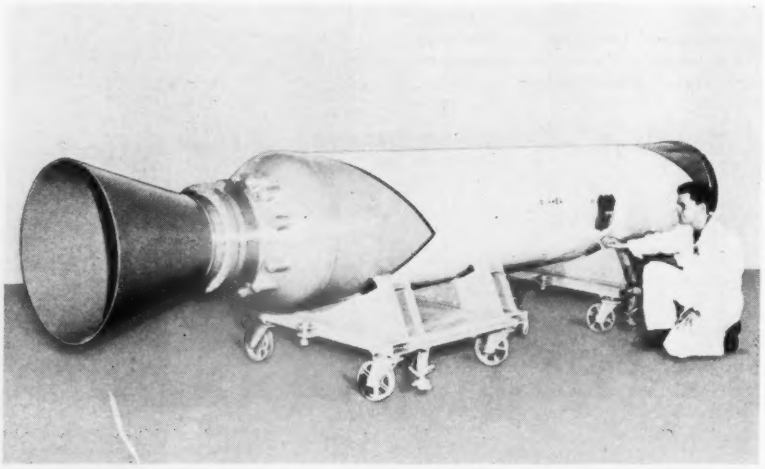
You will be working on projects under the leadership of experienced rocket men, using the finest and most modern facilities for research, development, and production. As you progress, you are given corresponding responsibilities. Thus, by on-the-job experience, you gather valuable knowledge while training.

In the Rocket Fuels Division alone, there are approximately 200 skilled scientists and engineers representing more than 1600 years of experience in rockets and related fields. Through an efficient interchange of technical information among the various departments of Phillips Petroleum Company, the Rocket Fuels Division can call upon specialists from among the company's 3000 scientists and engineers to assist in solving complex problems.

Those who join Rocket Fuels Division find moderately priced living conditions, excellent schools, and a variety of recreational facilities in central Texas. Opportunities at Rocket Fuels Division are limited only by ability and initiative.

Rocket Fuels Division offers salaries to match abilities and experience, an attractive retirement benefit plan, thrift plan, vacations, group insurance, as well as pleasant working conditions.

If you are interested in being considered for an opportunity to develop a profitable and challenging career in the rapidly expanding rocket field, and work with men who are tops in the field of rocketry, contact: Employment Office, Rocket Fuels Division, Phillips Petroleum Company, McGregor, Tex.



The Pusher rocket is one of a series of booster-type rockets successfully designed, developed, and test-fired by the Rocket Fuels Division of Phillips Petroleum Company at AF Plant 66, near McGregor, Tex. The rocket employs a propellant of the same type used in the M15 JATO rocket engine, which qualified for production under the Air Force's rigid requirements. This family of propellants, developed by Phillips, is made from such common petroleum-derived materials as carbon black, ammonium nitrate, and synthetic rubber. The Pusher is a rocket of the type that yields high thrust for short durations; however, it is not the largest rocket successfully tested by Phillips.

The Ramo-Wooldridge Corporation

5730 Arbor Vitae Street, Los Angeles 45, California

THE Ramo-Wooldridge Corporation conducts research, development, and manufacturing operations in the field of electronic systems for commercial and military applications, and in the field of guided missiles. The company is organized around a central group of scientists, engineers, and administrators who have unusual records of recent accomplishment in these fields. The principal company objective is to maintain a high level of competence in major systems development and engineering.

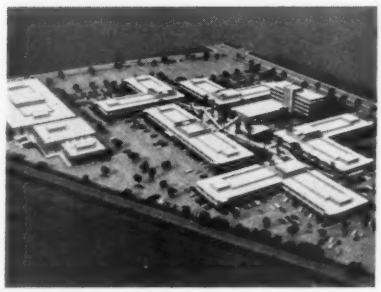
Both because of the national need and the inclination and experience of the key people, emphasis in The Ramo-Wooldridge Corporation is on the development of products having a high content of scientific and engineering newness. Prominent examples are the Interconnetintal and Intermediate Range Ballistic Missiles, Air Force programs for which R-W has over-all technical direction and systems engineering responsibility. Additional examples are advanced work in the fields of modern communications, digital computing, data processing, fire control, and navigation systems for the military; and automation, operations research, and data processing projects for business and industry. All of this development work is strengthened by a supporting program of basic electronic and aeronautical research.

All features of the organization and of the operational procedures of the company are designed to be as appropriate as possible to the special needs of the professional scientist and engineer.

The following paragraphs constitute a brief progress report on the current status of our growth and on the activities in which we are engaged.

Technical Personnel

Total R-W employment now numbers 2750, and of these 750 are members of the professional scientific and engineering staff, including 160 Ph.D.'s, 270 M.S.'s, and 320 B.S.'s or B.A.'s. A gratifying high percentage are men of broad experience and, occasionally, national reputation in their fields.



Facilities

The company's Los Angeles facilities, located in the International Airport area, consist of eleven buildings totaling 600,000 sq ft of modern research and development space. Three of these buildings, completed in the past two months, are the initial units of our entirely new 40-acre Research and Development Center, a model of which is shown above, which we believe will be one of the finest research and development facilities in the country. At least two additional buildings of the Center are scheduled for completion later this year. Nearby is the R-W flight test facility, including hangar, shop, and laboratories, located on a 7-acre plot at International Airport.

Financing

Adequate financing for our growth, as well as other important corporate advantages, were secured early by establishing strong ties with Thompson Products, Inc., one of the nation's most progressive large corporations. Arrangements have been made with Thompson for up to $20,000,000 of additional financing to cover the Ramo-Wooldridge expansion requirements of the next few years.

Manufacturing

Production has been under way in Los Angeles on some projects since the latter part of 1955. To provide for quantity production of electronic systems, a manufacturing plant is now under construction on a 640-acre site in suburban Denver, Colo. The initial unit of the plant, about 150,000 sq ft, is expected to be completed by early summer.

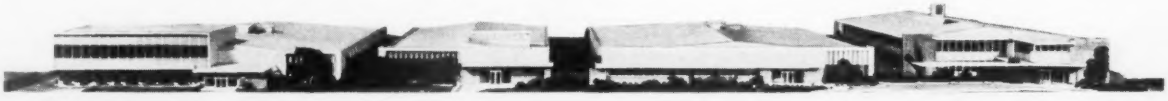
Fields of Activity

The technical areas available to a company specializing in advanced electronic systems and guided missiles work are numerous, and no attempt has been made to impose narrow limits on the areas considered suitable for future planning. Therefore the following list of fields simply outlines the kind of work that is currently under way and that is expected to continue and expand during the next several years:

- **Guided Missile Research and Development**
- **Aerodynamics and Propulsion Systems**
- **Communications and Navigation Systems**
- **Automation and Data Processing**
- **Digital Computers and Control Systems**
- **Airborne Electronic and Control Systems**
- **Electronic Instrumentation and Test Equipment**
- **Basic Electronic and Aeronautical Research**

For a copy of our booklet, "An Introduction to The Ramo-Wooldridge Corporation," or other additional information, write to:

Mr. D. L. Pyke,
The Ramo-Wooldridge Corporation,
5730 Arbor Vitae St.,
Los Angeles 45, California



Raytheon Manufacturing Company

Missile Systems Division

Hartwell Road, Bedford, Mass.

This modern plant is the headquarters of the Missile Systems Division. Located only 20 miles from Boston, it affords engineers the opportunity for either urban or suburban living.

Largest in New England

RAYTHEON is a unique organization. While it is the largest company in New England in the electronics industry, it has found through experience that the greatest progress can be made by decentralization. Hence, it is made up of several "Divisions" or "Operations," each with considerable responsibility for the success of its specific task. This method enabled Raytheon to establish an outstanding reputation in its field during World War II and the Korean War and has made possible further expansion of the Company and its activities since then.

Army, Navy

Raytheon is prime contractor for these missile systems—Army for Hawk I, Navy for Sparrow III. Over-all responsibility for the development of these systems and the production of missiles rests with us.

East and West

The Missile Systems Division has Massachusetts plants in Bedford, Lowell, Andover, and in Bristol, Tenn., supplemented by flight test facilities at Oxnard, Calif., and White Sands, New Mexico.

Growth Opportunities

Increasing demands for our engineering services and modern facilities have brought about a continual expansion of our professional personnel, providing exceptional opportunities for personal progress. Raytheon offers numerous advancement possibilities, interesting professional challenges, tuition support plan for engineering courses, regular salary review, adequate supporting technical personnel, liberal life and health insurance, paid vacations, and other employee benefits. Recognition of individual achievement is speedier at Raytheon than would be possible in a company with more centralized authority.

The success of the Missile Systems Division in weapons systems management has resulted in developmental contracts for future generations of guided missiles employing advanced techniques successfully demonstrated in both Hawk I and Sparrow III. In a period of ten years our division has grown from a small laboratory to an organization of over thirty-four hundred employees, including more than five hundred engineers. As a weapons systems contractor in the guided missile field, the Division has its own Aerodynamics, Structures, Hydraulics, Mechanical Design, Microwave, Circuit Design, and Systems Engineering groups.

Our present engineering work load, and the military requirements for more advanced missiles, present unlimited opportunities for engineers in all of the above fields.

For further information please write:

G. P. O'Neil
Raytheon Manufacturing Company
Missile Systems Division
Bedford, Mass.

This is the Shawsheen Mill, one of New England's mammoth plants recently acquired by Raytheon as manufacturing, office, and warehouse space to produce military equipment for the Army Ordnance Corps.

Reaction Motors, Inc.

66 Ford Road, Denville, N. J.

YOU, as an engineer or scientist who likes to put his advanced ideas into practice, will find rich rewards and full scope for your talent at Reaction Motors. Founder of the American rocket industry, Reaction Motors has never stopped growing. Here you can work with top engineers and scientists on high-level assignments, from original research to final test and production.

RMI—A Pioneer

Incorporated in 1941, Reaction Motors is a true pioneer in the rocket industry. From the very beginning, its products made possible important advances in applications of rocket power. RMI engines have been used in the Skyrocket X-1 and X-1A supersonic airplanes, the Lark guided missile, and the Viking missile which set major speed and altitude records. A pioneer that has fulfilled its early promise, RMI's growth continues to pace the rocket industry.

Current Expansion

Even more rapid expansion is now underway to develop new engines for the future, engines that are expected to surpass all previous records. A new multimillion dollar plant has been occupied and additional facilities are well beyond the planning stage. RMI's vitality and stability are reflected in its constantly increasing volume of business and employment at an all-time high.

Immediate Openings

Expansion has created additional openings at all levels for technical personnel who want careers that permit them to advance as far as their ability warrants. There are immediate openings for graduate engineers with experience or training in the following fields:

- Engine design
- Chemical kinetics
- Combustion phenomena
- Servo mechanisms
- Controls (hydraulic, pneumatic, electrical)
- Project engineering
- Instrumentation
- Applications engineering
- High temperature alloys
- Test
- Aerodynamics
- Fluid flow
- Nuclear applications
- Analog simulation
- Data reduction
- Thermostress and vibration
- Technical planning (advanced design)
- Proposals

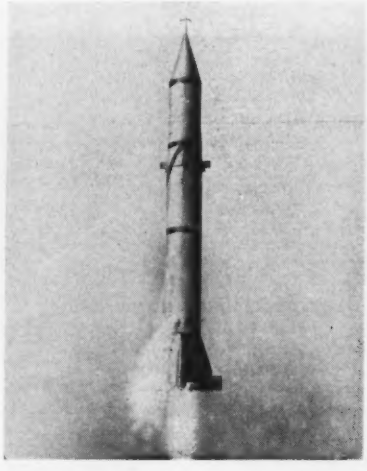
Top Salaries and Benefits

RMI pays top-scale salaries, as high as any in the industry. Because of exceptional opportunities for advancement, capable men who join RMI can look forward to increasingly higher earnings. RMI bulwarks employee security and job satisfaction through benefits such as paid vacations, a retirement program, hospitalization, insurance, tuition assistance, and other extras which are second to none in industry.

Attractive Living

RMI's location, in the beautiful lake region of northern New Jersey, offers an unusual blend of resort pleasures, suburban living, and urban advantages. RMI personnel can enjoy a variety of sports all year round without leaving the immediate area. They can choose any of several fine communities, all providing plentiful housing and excellent religious, cultural, and educational facilities. New York City, with unsurpassed urban advantages, is only 35 miles away.

Your career with RMI will have all the promise, the excitement, and the pride in accomplishment that mark the rocket industry itself. The present period of rapid expansion is the time to join RMI because men who come in now are in a particularly favorable position for future industry leadership. To find out how well you can do at RMI, write today, enclosing a resume of your education, experience, and salary requirements to the Supervisor of Technical Placement.



Navy Viking high-altitude research rocket powered by an RMI 20,000-lb thrust engine leaves launching platform

Aerial view shows general and administrative offices, laboratories and experimental shop; additional buildings and facilities, not shown in this photograph, house engineering, manufacturing and test activities

Rocketdyne

A Division of North American Aviation, Inc.

Canoga Park, California; Neosho, Missouri

AT ROCKETDYNE'S Propulsion Field Laboratory in the Santa Susana Mountains near Los Angeles, you'll hear a most impressive sound: the thundering roar of the most powerful mechanical and chemical device yet engineered by man—a large rocket engine. Only when you see one operate will you get the full technical implications of power for outer space.

Space power means developing rocket engines as small as a sports car, as powerful as Hoover Dam . . . with basketball-size components more powerful than a Diesel locomotive. Materials must be made to operate in temperature environments from −300 F to 5000 F, with machined tolerances of less than 0.0001 in.

You will work years beyond advanced textbooks in thermodynamics, fluid mechanics, heat transfer, dynamics analysis, high speed mechanics, physical chemistry, servomechanisms, and instrumentation. Whether you concentrate on one of these fields or coordinate several of them on a broad basis, you'll get experience practically unobtainable elsewhere.

There's challenge for those with advanced degrees as well as BS graduates. Men with advanced training are vitally needed in such work as research or preliminary design and analysis, or other advanced areas of analytical work in design and development, such as dynamics analysis, stress analysis or systems analysis.

If you have a BS degree, here are your opportunities:

Chemical Engineers: If your forte is theory or analysis you can get your teeth into heat transfer, thermodynamics, combustion, gas dynamics, fluid mechanics, propellant chemistry or systems engineering. If your bent is process work, operations and heavy equipment, you'll find scope in test engineering. It encompasses the most advanced combustion process ever conceived, and involves the latest techniques in development and utilization of manpower, equipment and facilities. The liquid propellant rocket engine is a highly automated chemical plant, and the Chem. E revolves around it all the way from corrosion to catalysis.

Mechanical Engineers: More ME's are employed here than any other degree. They work in advanced theoretical and creative phases of design and research; in practical test and development work covering a multitude of components needing imaginative structural and mechanical design; in advanced analytical phases of stress, dynamics, heat power and systems engineering. Probably every field of mechanical engineering known is represented at Rocketdyne.

Aeronautical Engineers: Needed in design or development of combustion devices, controls, turbomachinery and complete engine systems. The AE is invaluable in stress, lightweight design, aerodynamics and other areas. Too, he plunges deeply into one field or crosses over several, depending on his ability and interest. There's fascinating work in vibration, aerothermodynamics, reliability, many more. Light weight, high loads and low safety factors make the AE indispensable in rocket engineering.

Electronic or Electrical Engineers: We deal in high performance electrical and electronic systems, both airborne and ground; also power distribution, in each type of system. An interesting new area is dynamics analysis, involving analog simulation techniques. Another is servomechanisms, often in original and unique applications with broad future possibilities. For the EE, our Propulsion Field Laboratory offers what is probably the most extensive instrumentation facility of its kind, handling 10,000 items per second from some 200 pick-up points in each test stand. We are exploring every electronic field from semiconductors and transducers to communications and telemetering.

Physical Science Majors: Mathematicians will find a new frontier in the applied mathematics of space geometry, utilizing techniques of matrix algebra, theory of equations and analytical geometry. This is to establish the master dimensions of the rocket engine necessary to practical design, tooling, manufacture and assembly. Numerical analysis offers opportunities in digital computer programming. Dynamics analysis and design analysis embrace analog computer applications work. The statistical mathematician will find unlimited scope in reliability, performance analysis and instrumentation systems.

As a Physicist you may enter a variety of fields: preliminary analysis, systems analysis, applied mechanics, instrumentation, numerical analysis or research. The engineering physicist, in particular, is extremely valuable.

The Chemist will find his chief expression in physical chemistry, with some organic and inorganic work. We prefer advanced degrees in these areas: chemical kinetics, heat transfer, thermodynamics, gas dynamics, statistical mechanics, corrosion and organic synthesis. The work may be theoretical, experimental, analytical or applied, or a combination.

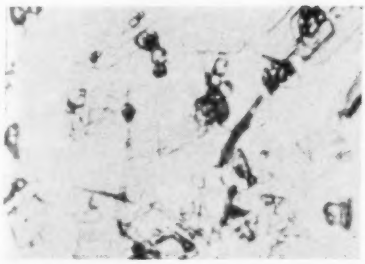
For More Information, send for your copy of "The Big Challenge," a 24-page booklet containing details on our work not published before. It is indexed for quick, factual reading. Write, specifying your degree, year of graduation, major interest:

A. W. Jamieson
Engineering Personnel Dept. JP
6633 Canoga Avenue
Canoga Park, California

Rohm & Haas Company

Redstone Arsenal Research Division

Huntsville, Ala.



Fundamental, integrated research directed toward those areas. . .

Organization

THE Redstone Arsenal Research Division of Rohm & Haas Company is a nonprofit division of this major chemical manufacturer, operated for the Army Ordnance Corps as a national service with the aim of making major advances in the field of solid propellant rocket science. A highly competent technical staff of approximately sixty scientists and engineers forms the nucleus of the organization. Supporting this group are a number of able laboratory and technical assistants, draftsmen, clerical, and secretarial employees. This support releases the full potential of the technical man by relieving him of routine or nontechnical work. The full strength of the Division is roughly two hundred and fifty.

The research program is fundamental, integrated, and flexible in approach. The major effort of the Division is constantly directed toward those phases of solid propellant rocket science which offer the greatest promise of major achievement. Approximately one half of the Division's effort is in basic research and long-range development programs, the rest being divided between immediate and near-term applications.

Scientific Opportunities

Many scientific disciplines are represented on the Division's technical staff. The outline below indicates these fields of training and some of the programs in which these talents are utilized:

Chemical Engineering

Design and economic evaluation of chemical processes; development of processes for promising new propellant compositions and their ingredients.

Pictures show crystals of a novel propellant ingredient.

Electronic Engineering

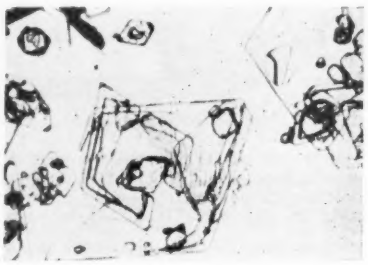
Design, development, and maintenance of electronic instruments based on new circuit design principles.

Mechanical Engineering

Analysis problems in heat transfer, fluid flow, elasticity, exterior ballistics, and weapons systems. Design, development, and testing of rocket and missile propulsion components and associated test equipment and test instrumentation.

Applied Mathematics

Application of mathematics to problems involved in interior and exterior ballistics, solution of equations, and mathematical analysis and interpretation of experimental programs.



. . .which offer the greatest promise, results in. . . .

Physics and Engineering Physics

Basic studies of interior and exterior ballistic phenomena—influence of heat transfer, fluid flow, and aerodynamic factors on rocket motor performance; measurement of physical properties of propellants and correlation of these properties with ballistic performance; design of novel experimental techniques.

Analytical Chemistry

Development of analytical methods for novel functional groups; analysis of propellant compositions and reaction products.

Physical Chemistry

Fundamental kinetic studies of reactions encountered in propellant ignition and combustion; thermal decomposition studies of novel compounds; basic investigations of influence of heat transfer, fluid flow, etc., on propellant burning in rocket motors.

Organic Chemistry

Basic chemistry of organic compounds with explosive potential; development of new synthetic methods and synthesis of new explosive compounds; interpretation of synthetic reaction processes through instrumental methods.

Organic Chemistry
Physical Chemistry
Polymer Chemistry

Fundamental studies in propellant chemistry; correlation of molecular structure with ballistic characteristics; laboratory scale compounding and evaluation of new propellant compositions; applications of polymer chemistry to solid rocket propellants.

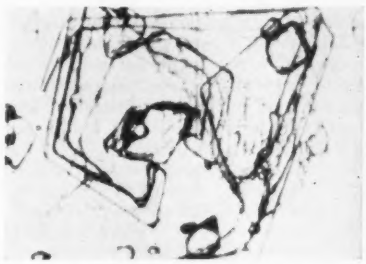
Location

The Redstone Arsenal Research Division is located in the mountains of northern Alabama, near the fast-growing city of Huntsville which now has a population of approximately 50,000. The nearby TVA lakes offer exceptional facilities for water sports and outdoor activities, while the Smoky Mountains and the Gulf Coast are within easy driving distance.

Benefits and Pay

The Redstone Arsenal Research Division is an integral part of Rohm & Haas Company, and employees enjoy the same opportunities for advancement and job security as employees throughout the company. Pay practices are competitive with the chemical industry.

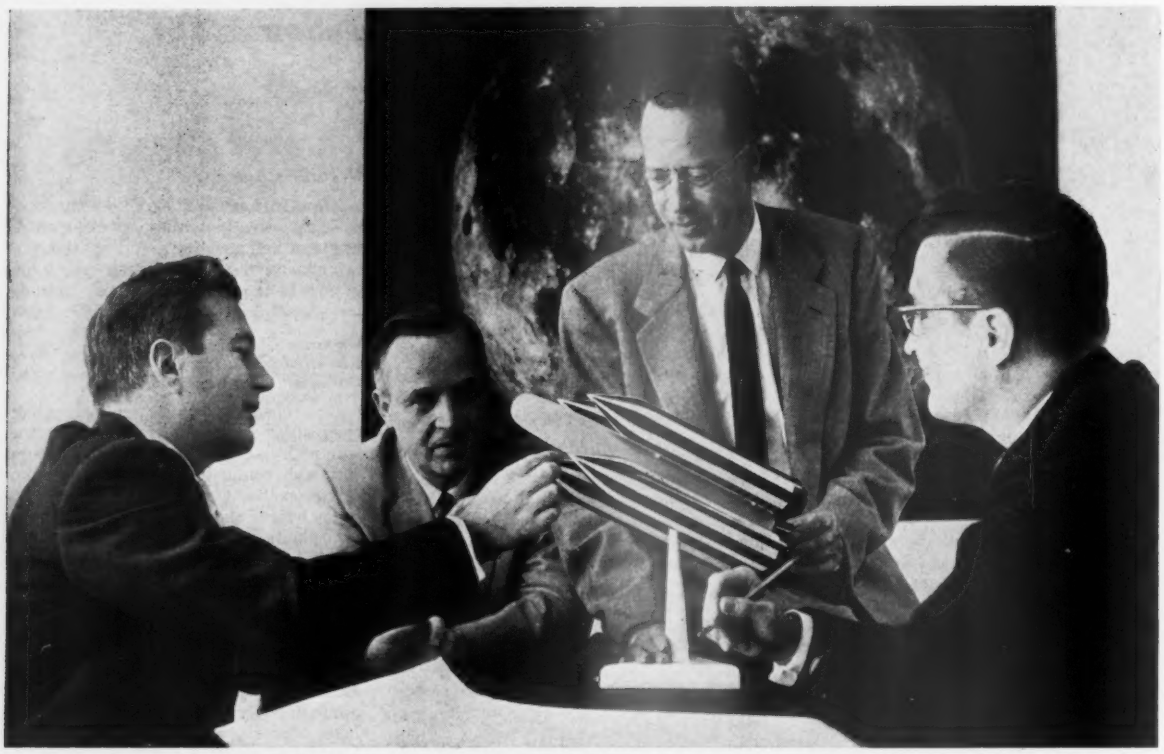
To those interested in rocket technology, this Division offers the opportunity for basic and applied research in a field of vital interest. Apply by letter, giving qualifications, to Personnel Department, Rohm & Haas Company, Redstone Arsenal Research Division, Huntsville, Ala.



. . . .major advances in the field of solid propellants

Systems Laboratories Corporation

15016 Ventura Boulevard, Sherman Oaks, Calif.



Dr. John L. Barnes (second from right), President of Systems Laboratories Corporation, discusses with members of his staff some of the problems involved in sending a manned missile to the moon. Left to right: Richard H. De Lano, Director of Systems Integration Division; Astrophysicist Dr. Lewis Larmore, Director of Super-Radiofrequency Sensors; Dr. Barnes; and Dr. James A. Marsh, Vice-President and Director of Radiofrequency Sensors.

SYSTEMS Laboratories Corporation, formed less than a year ago by a group of the country's leading scientists and engineers, is the first organization of its kind designed especially to undertake the research and development of interplanetary travel. Already established as one of the fastest-growing companies on the west coast, it offers unparalleled opportunities to qualified young men of vision and imagination who wish to take part in the most challenging adventure of our time: the actual exploration of outer space.

Headed by John L. Barnes, himself one of the world's leading authorities in the guidance and control of long-range missiles, SLC is wholly owned and directed by the scientists and engineers who comprise its staff and includes among its members and consultants the men who helped develop the Navaho, Falcon, ICBM, and other of the nation's foremost guided missile systems. Among its top-priority projects are contracts from Republic Aviation Corp. and other major agencies in the field of extra-atmospheric missiles, all closely allied with the corporation's primary purpose: feasibility and preliminary design studies of interplanetary vehicles. Dr. Barnes and his associates are confident that man's first flight to the moon can be accomplished within the next fifteen years if sufficient effort is devoted to the task. It is the company's principal objective to help organize and direct this effort.

The fields of inquiry and activity in which SLC is currently engaged include:

Aeronautics: Aerodynamics

Applied mathematics:
Machine computation
Mathematical statistics

Automation:
Autonavigators, Autopilots

Electromechanical & Electronic Engineering:
Antennas, Communications, Computers
Instrumentation, Navigation, Propagation
Radar

Nucleonics: Reactors

Physics: Cosmic ray
Super-Radiofrequency
Upper atmosphere

Propulsion: Ramjets, Rockets

Spacenautics: Orbits, Trajectories

Systems Engineering:
Operations analysis
Systems synthesis

Science, mathematics, and engineering students who are interested in any of these fields and who are seeking a career with unlimited opportunity for advancement and achievement, are cordially invited to submit their résumés directly to Dr. Barnes at the address above. Students in the top 10 per cent of their class may be eligible for an SLC Graduate Scholarship which will permit them to continue their postgraduate education at SLC's expense while actually working on some of the most advanced and stimulating assignments of the Space Age. Information on the scholarship program will be forwarded on request.

As well as top salaries and an unusually liberal benefit program, Systems Laboratories Corporation provides the incomparable advantages of living in one of Southern California's most desirable residential and recreational communities, only minutes away from the center of Los Angeles in the famous San Fernando Valley.

Thiokol Chemical Corporation

Rocket Divisions

Home Office: Trenton, N. J.

Introduction

ENGINEERS and scientists at the Rocket Divisions of Thiokol Chemical Corporation design and develop propulsion units for some of our nation's leading weapons and research vehicles. Rocket engine development at Thiokol has yielded propulsion units for the Falcon, Matador B, Nike B (Nike Hercules), Lacrosse, Terrapin, and RV-A-10 missiles. Among the propulsion units developed by Thiokol's team are some of the largest solid propellant rocket engines ever built.

Ever since Thiokol marketed the first synthetic rubber produced commercially almost 30 years ago, the company has been expanding to meet the ever-changing needs of science and industry. Today rocket engine and propellant research development, testing, and production at Thiokol offer a wide variety of challenging assignments for those interested in becoming a part of the vastly important field of missile propulsion. Thiokol professional personnel have been brought together from many fields to form a uniquely close-knit, well-coordinated association directed toward increasingly greater achievements. The skill, imagination, and individual as well as collective enthusiasm of this group have been responsible for Thiokol's position as one of the leaders in the field of advanced solid propellant propulsion systems.

Development of successful power plants stems largely from Thiokol's "system's concept" of rocket engine design. In developing each propulsion unit, engineers work closely with the missile prime contractor to see that requirements such as guidance system impact and vibration resistance, center of gravity locations, fin and warhead attachments, and other overall missile problems are met. Application of this concept results in a propulsion unit that is an integral part of the missile. Since each propulsion unit is designed for a specific purpose, the engineer is faced with ever-changing problems in supplying the highest performance, lightest weight, and most reliable and rugged power plant for a specific application.

Locations

At the present time, Thiokol operates government-owned facilities at Redstone Arsenal, Huntsville, Ala., and at Longhorn Ordnance Works near Marshall, Tex.; company-owned facilities are at Elkton, Md., and Tremonton, Utah.

At its Redstone Division over 1000 employees are engaged in the development of the most effective solid propellant systems known. The continuing growth of programs in propulsion systems development has created openings for technically trained individuals interested in work which constantly challenges the imagination and offers maximum incentive for personal achievement.

At the Elkton Division outstanding contributions to modern rocketry are continually being made. Increasing demands on the Elkton Division resulting from successful achievements have provided opportunities for engineers interested in working on advanced rocket systems.

Manufacturing of Thiokol rocket engines is now under way at what may be the country's largest and newest facility designed exclusively for the production of solid propellant rocket engines—the Longhorn Division. Thiokol rocket groups have designed, planned, and directed the construction of this unique plant. Here qualified technically trained individuals are continually in demand to keep pace with rocket engine developments.

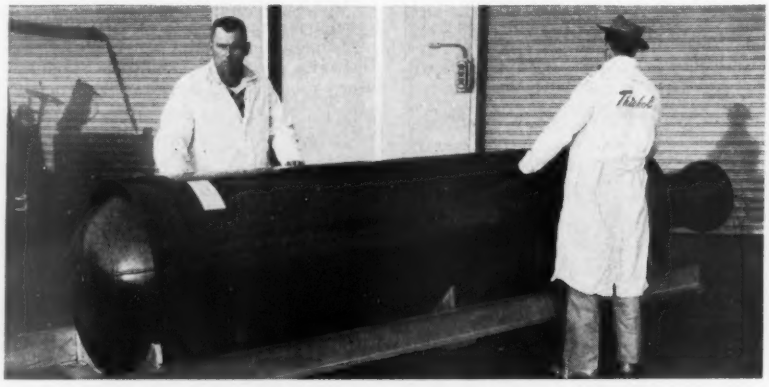
Future

Rarely does any industry offer better opportunities to professional scientific personnel than the rocket industry. Few companies offer a more diversified program with greater benefits than does Thiokol Chemical Corporation. With the full realization that relatively few individuals have gained experience in rocketry, Thiokol has instituted programs whereby engineers and other scientific personnel are encouraged to adapt their experience and training to the new and rapidly expanding rocket industry. Permeating the entire Thiokol organization is the concept that the company is only as good as its employees. Individuality and initiative are encouraged; talent and achievement are recognized. The team spirit of the organization inspires both confidence and enthusiasm. The extremely low turnover of the company's employees can be attributed, in part, to these factors.

The company's faith in the future is exemplified by the recent purchase of a 11,000-acre site near Salt Lake City, Utah, for rocket engine development and production facilities. Construction at this plant is under way and operations are expected to commence in the near future. Establishment of this plant will also create the need for additional technically trained individuals in all fields.

For additional literature on Thiokol's rocket operations, write to one of the following rocket divisions or to Thiokol's home office at Trenton, N. J.:

Thiokol Chemical Corporation, Redstone Division, Huntsville, Ala.
Thiokol Chemical Corporation, Longhorn Division, Marshall, Tex.
Thiokol Chemical Corporation, Elkton Division, Elkton, Md.



One of the large solid propellant rocket engines manufactured by Thiokol Chemical Corporation

Thompson Products, Inc.

Accessories Division

23555 Euclid Avenue, Cleveland 17, Ohio

What We Make

THE Accessories Division of Thompson Products, Inc., sponsor of the Thompson Trophy Race, is devoted exclusively to the development and manufacture of rocket and aircraft accessory equipment.

The Division does a complete development and production job. It takes the inception of ideas through design, drafting, model manufacture, development testing, manufacturing, and service. The Division manufactures auxiliary power units, turbine-driven rocket propellant pumps, air turbine-driven fuel pumps, aircraft booster pumps, high-pressure fuel pumps, speed and flow control units, and hot air turbine power drives.

Facilities and Abilities

Tomorrow's rocket and aircraft accessories are developed in a $12 million development laboratory located at the Tapco plant, Cleveland. This facility includes an available high-pressure, high-temperature air supply of 2100 lb per minute. The total laboratory floor space is 60,000 sq ft; about half the space is devoted to test and half to supporting equipment. There are an extensive fuel storage area, walk-in environmental chambers, dynamometers up to 500 hp, a high-capacity altitude exhaust system, and an instrument department to meet all development measuring needs.

Ground has been broken on a 1000-acre tract in Franklin County, near Roanoke, Va., for a $10-million advanced aircraft and rocket accessories research and development testing center.

The Division History

The Division was founded in 1941 when the company, numbering 10,391 employees, set up divisions to increase operating efficiency. Starting with aircraft vane pumps and booster pumps, the proprietary products became an increasingly important part of the Division's growth. The Division pioneered the tank-mounted booster pump and is today the leading manufacturer. In 1950, air turbine pumps, air drives, and high-pressure fuel pumps were added. In 1955, the Division added auxiliary power units.

Today the total company employment has reached 21,218. The Division has grown to 2200 persons with research facilities at Cleveland; Inglewood, Calif.; and Portland, Ore. Service facilities are at Cleveland; Hartford, Conn.; Inglewood, Calif.; and Seattle.

Security

This steady growth company provides a funded retirement plan which, with social security, can amount to 40 per cent of your five highest earning years. Hospital, surgical, and low-cost group life insurance is sponsored by the company and is available to all employees. The company's wage structure is keyed to the Department of Labor's cost-of-living index so that "cost of living" payments proportional to this index are made in addition to the regular salary. Systematic salary review periods insure that all technical employees are paid commensurate with their performance and growth.

Since the founding of the company in 1901, there has never been a strike or interruption of operations because of a labor problem.

Recreational Advantages

Located in Cleveland, the plant is within easy driving distance of one of Ohio's most beautiful residential areas. Cleveland is a richly endowed cultural center and has every recreational facility. The Cleveland Symphony Orchestra and Museum of Art are internationally famous. In addition, the company sponsors its own recreational program, embracing hunting, fishing, chess, bowling, golfing, baseball, orchestra, and choir activities.

The Division is located within a few miles of Case Institute of Technology and Western Reserve University where graduate courses can be taken. The company supports undergraduate and graduate scholarships. The company and universities have established programs to give technical employees every assistance in furthering their education.

A Career for You?

The future is bright at Thompson. A number of power unit development programs are now in progress. Aggressive development engineering has new products to maintain a rapidly expanding business.

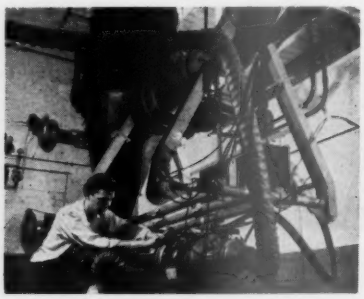
The Division offers opportunities in all these fields:

(1) Mechanical design
(2) Applied mechanics
(3) Fluid mechanics
(4) Combustion
(5) Servomechanisms
(6) Stress analysis
(7) Test

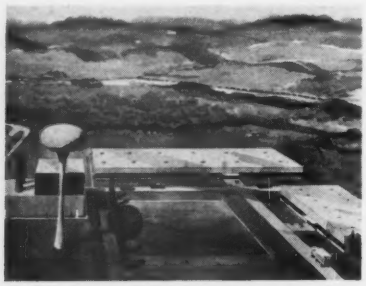
The engineer has the opportunity to follow a project all the way from the idea phase to production. This broad base of experience is such that the development engineer can progress into a specialized engineering field, project supervision, production engineering, or engineering sales, etc. For those who are interested in management and show promise in this area, the company conducts a one-year management training course.

Our stockholders' report will be sent to you upon request. Address all inquiries to Dr. John D. Stanitz, Chief Engineer, Accessories Division, Thompson Products, Inc., 23555 Euclid Avenue, Cleveland 17, Ohio.

Aerial view of the development laboratory at the Cleveland plant



Altitude test installation of air turbine drive



Advanced accessories testing center under construction near Roanoke, Va.

United Aircraft Corporation

Hamilton Standard Division

Windsor Locks, Connecticut

Equipment for a New Era

NO SINGLE factor more accurately reflects the onrushing rise in aircraft and missile performance than the parallel progress of the highly specialized equipment required to operate these new aircraft and missiles. When the gas-turbine engine and rocket propulsion brought unprecedented gains in aircraft speeds and altitudes, they also brought demands for equipment undreamed of only a few years ago.

At Hamilton Standard in Windsor Locks, Connecticut, the drive to meet these demands is sparked by the most intensive engineering program in the company's history backed up by a whole new build-up of development laboratory facilities. And it is characterized by the opening up of hundreds of new engineering jobs—opportunities unlimited for the young engineering graduate of today.

Gratifying Facilities

Laboratories for pneumatics, hydraulics, electronics, metallurgy, vibration, mechanics, chemistry and combustion, as well as exceptional computing, analogue and wind tunnel facilities—these form the physical background for the birth of such vital Hamilton Standard products as air conditioning systems, jet engine starters and fuel controls, auxiliary power packs, hydraulic pumps and pneumatic valves.

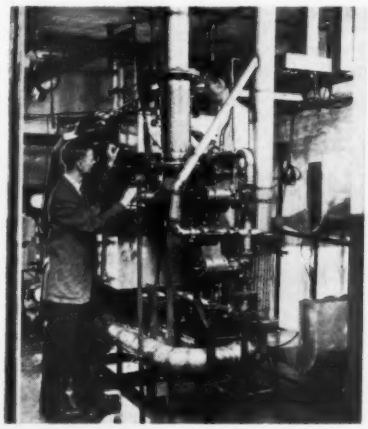
These laboratories come naturally to a company that long since made its mark as a pioneer. Many of the great gains in aircraft performance, dependability, economy and safety since the early 1930's would have been impossible without Hamilton Standard's propeller advances. Today's new laboratories, therefore, are but the outward marks of a company where the accent has always been—must always be—on the future.

"Wherever Man Flies"

For more than 35 years, Hamilton Standard propellers have been known, as the company slogan says, "Wherever Man Flies." The same situation is fast becoming a fact with the company's aircraft equipment products. Scarcely six years after Hamilton Standard produced its first equipment item, one or more of its five basic jet products either were installed in or specified for some 40 different aircraft types. These ranged from supersonic fighters and guided missiles to the largest and fastest jet bombers, including the Convair B-58, first supersonic bomber in America.

Jet Equipment Division

Most of the company's engineering effort and more than a third of its manufacturing area are devoted to the new jet age products. The steady rise of these products brought them to the point in 1956 where they accounted for over 30 per cent of the company's annual sales volume.



As a matter of fact, the equipment sales exceeded the company's total propeller sales for 1948, the year Hamilton Standard first decided to diversify its product line by entering the equipment field.

Construction of a new factory building for production of jet engine fuel controls; establishment of an engineering branch in St. Petersburg, Fla.; purchase of an aeropneumatics company to round out its own position in the air conditioning field; establishment of a new and integrated electronics department; development of many new machines and tools, and numerous realignments of its production organization and layout—all these are but a few evidences of the company's advances in the aircraft equipment field.

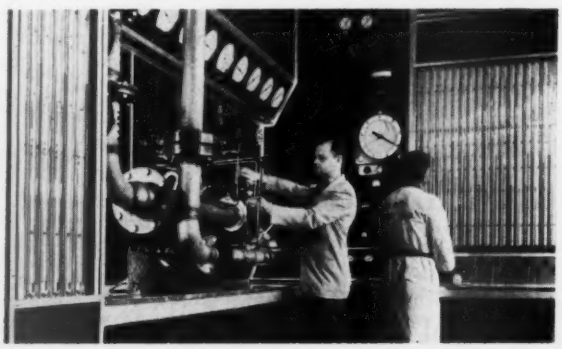
Visibility Unlimited

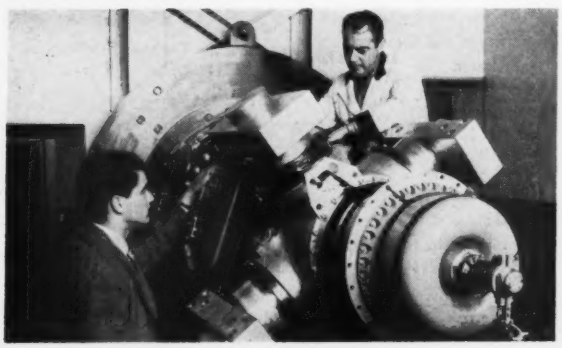
Meanwhile, both in the United States and abroad, aircraft are operating with their engines started, their fuel metered, their cabins and other compartments cooled, their landing gear, flaps and controls actuated by equipment designed and built at Hamilton Standard's modern plant in Connecticut.

Hamilton Standard's achievement in designing, developing and manufacturing its varied line of equipment for jet aircraft is a story of genuine progress in a few short years. Yet the larger story is one of opportunity—for Hamilton Standard and for its fast-growing engineering department. For it is all too clear that the future promises not only far greater problems, but far greater successes.

Openings

Exceptional career openings in design, development, analysis, metallurgy, liaison, vibration, checking, drafting. Unexcelled benefits including tuition-assisted post-graduate study. Send a résumé of your education and experience to Kell Smith, 49 Bradley Field Road, Windsor Locks, Connecticut.





*Faculty Members Who Will Distribute Careers Supplement**

Academy of Aeronautics
Ralph Hautau

University of Alabama
Colgan H. Bryan

Alabama Polytechnic Institute
Robert G. Pitts

Alfred University
W. G. Lawrence

American International College
Jesse O. Richardson

Amherst College
Science Department

University of Arkansas
M. E. Barker
N. H. Barnette

Polytechnic Institute of Brooklyn
Vito D. Agosta
T. P. Torda

Bucknell University
George A. Ireland
Merle M. Odgers
Hugh D. Sims

University of Buffalo
Roger Smith

University of California
A. K. Oppenheim

University of California at Los Angeles
Andrew F. Charwat
H. S. Seifert
Myron Tribus

California Institute of Technology
Frank E. Marble
Fritz F. Zwicky

California State Polytechnic College
J. O. Richardson

Canisius College
Herman A. Szymanski

Carnegie Institute of Technology
David H. Archer
C. E. Wangeman
E. M. Williams

John Carroll University
L. C. Sabin

Case Institute of Technology
Henry Burlage, Jr.
J. R. Hooper

Chrysler Institute of Technology
R. W. Rockefeller

University of Cincinnati
Odin Elnan
R. E. Peters

University of Colorado
Willard Edwards
K. D. Wood
W. K. Woods

Colorado Agricultural and Mechanical College
John E. Dean
Donald N. Zwiep

Columbia University
Hans Bleich
John R. Ragazzini

University of Connecticut
Dean of Engineering

Cornell University
J. L. Munschauer
W. R. Sears

Dartmouth College
James A. Browning

University of Delaware
James I. Clower
W. W. Hagerty
Kurt Wohl

University of Denver
Louis Breternitz
C. M. Knudsen

University of Detroit
S. J. Hirschfield
Donald J. Kinney
L. S. Kowalczyk
Kenneth E. Smith
John J. Uicker

Detroit Institute of Technology
L. L. Henry

Fenn College
M. B. Robinson

University of Florida
A. C. Kleinschmidt

General Motors Institute
Benjamin J. Ruddock

Georgia Institute of Technology
Thomas W. Jackson
William Meese Newton

Harvard University
Arthur E. Bryson

Haverford College
Gilbert F. White

Hillyer College
Jacob Koton

University of Houston
F. M. Tiller

University of Illinois
A. I. Andrews
P. U. Chapman
W. McCloy
N. A. Parker
H. S. Stillwell

Illinois Institute of Technology
T. A. Budenbolzer
Frank D. Carvin
Gail T. Flesher
E. C. Kubicek

Indiana Technical College
B. L. Dow

Indiana University
Richard Kramer

Iowa State College of A. and M. Arts
E. W. Anderson
L. R. Hillyard

Jacksonville University
J. B. Fleek

The Johns Hopkins University
F. H. Clauser
G. H. Dieke
R. E. Gibson
Ferdinand Hamburger, Jr.
W. S. Koski

University of Kansas
T. DeWitt Carr

Kansas State College
A. H. Duncan
R. M. Kerchner

University of Kentucky
E. E. Elsey
Karl O. Lange
H. Alex Romanowitz

Lafayette College
Ralph C. Hutchinson

Lamar State College of Technology
L. B. Cherry

LaSalle College
E. Stanislaus

Lawrence Institute of Technology
M. M. Ryan

Lehigh University
Frank Kreith
Martin D. Whitaker

University of Maryland
H. D. Cather
L. J. Hodgins
Clifford L. Sayre, Jr.
Charles A. Shreeve, Jr.
S. F. Singer

University of Massachusetts
George A. Marston

Massachusetts Institute of Technology
Paul Sandorff
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Jay A. Bolt
Richard G. Folsom
Gordon J. Van Wylen
Alexander Weir, Jr.
J. G. Young

Michigan College of Mining and Technology
Leo F. Duggan
Frank Kerekes

Michigan State University
Jack Breslin
C. F. Gurnham
L. C. Price

University of Minnesota
C. C. Chang
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Robert Eastman

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A. W. Schlechten
W. T. Shrenk

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New Mexico College of A. and M. Arts
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G. N. P. Leetch

Princeton University
Martin Summerfield

Purdue University
F. L. Cason
Noland Cooper
H. M. DeGroff
Maurice J. Zucrow

Rensselaer Polytechnic Institute
Joseph V. Foa

University of Rhode Island
Warren M. Hagist

Rice Institute
Janie Ross

University of Rochester
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Rollins College
D. W. Carroll

St. Louis University
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* The colleges and schools listed will receive copies of the Supplement directly. Others will receive quantities through the 34 ARS Sections. Any college or high school faculty member or student who wishes additional copies is invited to write to JET PROPULSION, 500 Fifth Avenue, New York 36, N. Y. Copies will be sent free as long as the supply holds out.

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Huntsville H. S.

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San Diego City Schools

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Windsor
Loomis Institute

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Fort Wayne
Central H. S.
Elmhurst H. S.
North Side H. S.
South Side H. S.

Mishawaka
Mishawaka H. S.

South Bend
John Adams H. S.
Central H. S.
Riley H. S.
St. Joseph H. S.
Washington H. S.

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Cony H. S.

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Belmont H. S.

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Boston English H. S.
Chauncy Hall

Brookline
Brookline H. S.

Everett
Everett H. S.

Framingham
Framingham H. S.

Gloucester
Gloucester H. S.

Lynn
Lynn English H. S.

Medford
Medford H. S.

Milton
Milton Academy

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Johnson H. S.

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Roslindale H. S.

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Sharon H. S.

Shirley Village
Shirley Village H. S.

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St. Marks School

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Classical H. S.

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Lincoln-Sudbury Regional H. S.

Waltham
Waltham H. S.

Winthrop
Winthrop H. S.

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Allen Park H. S.

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Berkeley H. S.

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Birmingham H. S.

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Clawson Board of Education

Detroit
Detroit Board of Education

Ferndale
Lincoln H. S.

Grosse Pointe
Grosse Pointe Public Schools

Harper Woods
Harper Woods School District

Hazel Park
Hazel Park Board of Education

Highland Park
Highland Park H. S.

Livonia
Livonia Public Schools

Oak Park
Oak Park H. S.

Royal Oak
Royal Oak Dondero H. S.
Royal Oak Kimball H. S.

Trenton
Trenton Public Schools

Warren
Warren H. S.

Wayne
Wayne Public Schools

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Edison H. S.
Henry H. S.
Marshall H. S.
North H. S.
Roosevelt H. S.
South H. S.
Southwest H. S.
Washburn H. S.
West H. S.

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Clayton H. S.

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Salem H. S.

St. Louis
Ladue H. S.

University City
University City Senior H. S.

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Andover
Proctor Academy

Exeter
The Phillips Exeter Academy

New Hampton
The New Hampton School

New Ipswich
Appleton Academy

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Atlantic City H. S.

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Bayonne, H. S.

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Belleville H. S.

Bergenfield
Bergenfield H. S.

Bloomfield
Bloomfield Senior H. S.

Bridgeton
Bridgeton H. S.

Butler
Butler H. S.

Caldwell
Grover Cleveland H. S.

Camden
Camden H. S.
Woodrow Wilson H. S.

Carteret
Carteret H. S.

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Hightstown H. S.

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Dickinson H. S.
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Kearny H. S.

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Lodi H. S.

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Lyndhurst H. S.

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Millville H. S.

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Montclair Senior H. S.

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Morristown H. S.

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New Brunswick H. S.
Rutgers Preparatory School

* See footnote p. 42-S.

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Barringer H. S.
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Essex County Technical H. S.
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Newton H. S.

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Rahway H. S.

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Rockaway Regional H. S.

Roselle
Abraham Clark H. S.

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Somerville H. S.

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H. G. Hoffman H. S.

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Teaneck Senior H. S.

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Weehawken H. S.

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West Orange Senior H. S.

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Westfield H. S.

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Woodbury Senior H. S.

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Wood Ridge H. S.

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Bayside H. S.

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Niagara Falls H. S.

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John Adams H. S.

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Membership Information
American Rocket Society, Inc.

500 Fifth Avenue, New York 36, N. Y.

THE AMERICAN ROCKET SOCIETY is one of the most rapidly growing professional engineering societies in the United States. Its membership, now 5000, was 1007 in 1952.

ARS is devoted to the advancement of jet propulsion and allied sciences in the fields of rockets, guided missiles, aircraft, and space vehicles. Its members include engineers, physicists, chemists, metallurgists, mathematicians, technicians, and others interested in the advancement of these fields.

The SOCIETY was organized on March 21, 1930. During its early years, experimental rocket development was the principal activity of the members, leading to the formation of the country's first rocket manufacturing companies. Dr. Robert H. Goddard, father of American rocketry, was one of the Society's early members.

Currently, ARS serves its field and its members through sectional, regional, and national meetings; publications; technical committees; and student chapters.

The scope of the Society's interest covers propulsion, combustion, instrumentation, guidance and control, high temperature materials, upper atmospheric research, structures, fuels and propellants, heat transfer, aerodynamics, aerothermodynamics, hypersonics, astronautics, space law, and other related technical fields.

Sections

There are ARS Sections in most of the centers of rocket, missile, and aircraft activity throughout the country. Sections are self-governing and receive financial assistance and supplies from the national office. Section meetings are usually held monthly, and consist of lectures, films, symposia, round-table discussions, field trips, plant visits, and social activities. Existing Sections include:

Alabama
Antelope Valley
Arizona
Central Colorado
Central Texas
Chicago
Cleveland-Akron
Columbus
Connecticut Valley
Detroit
Florida
Fort Wayne
Indiana
Maryland
National Capital
New England
New Mexico-West Texas
New York
Niagara Frontier
North Texas
Northeastern New York
Northern California
Pacific Northwest
Philadelphia
Princeton Group
Sacramento
St. Joseph Valley
Saint Louis
San Diego
Southern California
Southern Ohio
Twin Cities

Publications

JET PROPULSION, the Journal of the AMERICAN ROCKET SOCIETY, is published monthly and sent to all members. It contains technical and general interest articles as well as world news of rockets, guided missiles, astronautics, and Society activities. It has been described by authorities in the field as follows:

"I am especially satisfied by the fact that on one side, the research man finds in the JOURNAL first-class scientific articles. On the other hand, the JOURNAL does not neglect the needs of practical engineers and persons engaged in management of companies manufacturing rockets, jet engines, missiles and aircraft or aircraft components in general."

Theodore von Kármán

"I believe the JOURNAL is largely responsible for the large increase in membership in the SOCIETY in this area and particularly among the technical and scientific staff people of the aircraft engine companies in Southern California."

C. C. Ross

"Every time I find a new issue of JET PROPULSION in my mail I drop anything else, and I know that it is the same with my associates."

Wernher Von Braun

Student Chapters

Authority for the establishment of Student Chapters at recognized university-level educational institutions was recently granted. Information on the procedure for establishing a Student Chapter can be obtained from Membership Chairman, AMERICAN ROCKET SOCIETY, 500 Fifth Avenue, New York 36, N. Y.

Helicopter show featured one Section meeting. Members also saw liquid rocket firing. Demonstrations took place at eastern plant.

Milton Rosen receives Wyld Award from Mrs. Wyld at ARS banquet

Awards

Robert H. Goddard Memorial Award for outstanding work in liquid propellants.

C. N. Hickman Award for outstanding work in solid propellants.

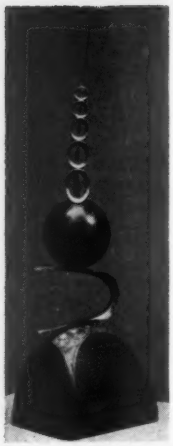
G. Edward Pendray Award for outstanding contribution to the rocket and jet propulsion literature.

James H. Wyld Memorial Award for outstanding application of rocket power.

ARS Astronautics Award for outstanding contribution to the advancement of space flight.

ARS Chrysler Award, a $1000 stipend to be used by a student for educational purposes.

ARS Student Award for the outstanding student paper on jet propulsion or a related subject.

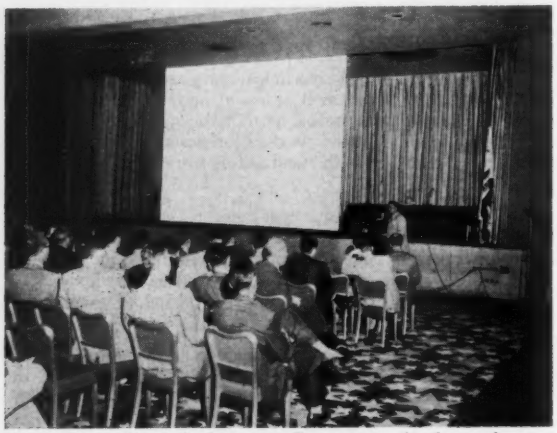


ARS Astronautics Award

Technical Committees

The Society has recently formed six committees whose chief purpose is to advise the Program Committee and the editorial staff of Jet Propulsion on subjects within their fields of specialization. Another new committee, on Monopropellant Test Methods, has published its first two reports on tests recommended for the field. All of the committees are listed at right.

Instrumentation and Guidance
Liquid Rockets
Ramjets
Monopropellant Test Methods
Space Flight
Propellants and Combustion
Solid Rockets



Discussions of technical papers offer opportunity for exchanges of ideas

National Meetings

Technical sessions, symposia, field trips, luncheons, and banquets are features of the regional and national meetings sponsored by the Society. The tentative schedule of forthcoming meetings is:

April 3–6, 1957—Spring Meeting, Washington, D. C.

June 10–13, 1957—Semi-Annual Meeting, San Francisco

Aug. 25–28, 1957—Gas Dynamics Symposium, Northwestern University, Evanston, Ill.

Dec. 2–6, 1957—Twelfth Annual Meeting, New York

March 17–20, 1958—Spring Meeting, Dallas

Membership

There are four grades of individual membership—Fellow Member, Member, Associate Member, and Student Member. Qualifications for the latter three grades are detailed on the reverse side of the application form attached. Fellow Members are individuals elected yearly by the Board of Directors from a list of persons who have distinguished themselves in the field of rocket or jet propulsion or who have contributed outstanding service to the Society.

Corporate Members consist of educational, scientific, or industrial organizations which may choose this method of expressing their interest in the development or application of rocket or jet propulsion, and which are considered acceptable by the Board of Directors. Each Corporate Member is entitled to five representatives with the rights and privileges of Members. Organizations interested in Corporate Membership should contact the Executive Secretary.

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Treasurer	Robert M. Lawrence
General Counsel	Andrew G. Haley

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Wernher von Braun, 1957

American Rocket Society, Inc.

500 Fifth Avenue, New York 36, N. Y.

Application for Membership

FOR OFFICE USE ONLY

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To the Membership Committee:

I hereby apply for membership in the AMERICAN ROCKET SOCIETY, INC., and enclose $———— as my annual membership dues, $5.00 of which is for a year's subscription to JET PROPULSION, the Journal of the AMERICAN ROCKET SOCIETY. The information given herewith is correct to the best of my knowledge.

Check type of membership desired (see other side for qualifications)

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☐ ASSOCIATE MEMBER—annual dues $15.00
☐ STUDENT MEMBER—annual dues $5.00

Date ————————

Signature in Full ————————

Sign with pen—Do not use initials

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Other Technical Organization Memberships ————

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Secondary School ———— Date ————

College or University ———— Date ————

Major Subject ———— Degree Received ———— Date ————

Names of other Technical Schools or Colleges ————

Additional Degrees ———— By Whom Conferred ———— Date ————

References

Name three and include addresses. Include at least one ARS member if possible.

————

————

————

(Over)

Professional Record (Optional for Student Member Applicants. If space is inadequate add supplementary sheet of this size.)

Dates: from	to	Names and addresses of past employers. Your positions, duties and responsibilities.

Memberships

MEMBER: Members shall consist of engineers and scientists who are actively engaged in the development or application of rocket or jet propulsion, other persons who have been working on the development or application of rocket or jet propulsion for at least four years and who hold or have held responsible positions in these fields, and such persons as may be deemed eligible for this class of membership by the Board of Directors by virtue of their outstanding accomplishments in other fields and their unusual interest in the purposes of the SOCIETY.

ASSOCIATE MEMBER: Associate Members shall consist of persons, other than students, who are actively interested in the development or application of rocket or jet propulsion.

STUDENT MEMBER: Student Members shall consist of persons not less than 17 years of age whose principal occupation is study at a recognized educational institution or who are serving as enlisted personnel in the Armed Forces of the United States, and who are interested in the development or application of rocket or jet propulsion.

CORPORATE MEMBER: Corporate Members shall consist of educational, scientific, or industrial organizations who may choose this method of expressing their interest in the development or application of rocket or jet propulsion, and who are considered acceptable by the Board of Directors. Each Corporate Member shall be entitled to five representatives with the rights and privileges of Members. (Write for special Corporate Membership application form.)